

DEVELOPMENT OF CREATIVE AND INNOVATIVE DESIGN TECHNIQUES THROUGH ADVANCED INFORMATION TECHNOLOGY METHODS

FEDA MOHAMMED MUNTHER SALAH

PhD THESIS

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**A thesis submitted to De Montfort University, Faculty of Arts and Design in
partial fulfillment of the requirements for the degree of Doctor of
Philosophy - May 2008**

ABSTRACT

Design is considered a goal-oriented, problem-solving activity that relies on several key elements namely: human experience, creative thinking and related knowledge. These three key elements if integrated within any design development and accompanied by suitable design methodologies made possible by design computation and advancements in computer technologies can achieve the most creative and competitive results.

The reviewed previous research studies discussed specific areas but lacked holistic perspective on creative design systems necessary to support creative design teams throughout the entire design process. The main aim of this current research is to address the issue of creative thinking in design from a holistic perspective. Furthermore, to establish a new approach for applying evolutionary computing and visualizing technology in support of creative design thinking among design teams.

To achieve this main aim several objectives have been accomplished: (1) investigating existing related areas of research through literature review and interviews, (2) developing a holistic approach for creative design thinking, (3) constructing the overall architecture for a creative design environment to support creative design thinking, (4) developing a novel design computational model to enhance creative design thinking, (5) developing a methodology for creative design model which integrates various necessary elements (6) developing a working prototype using web-technologies, and design computational methods, and (7) validating the developed system through the application of a case study.

The developed system comprises knowledge databases, a set of creative design tools, individual and team design environment, a user interface, and five design modules namely: preparation, concept generation, development, evaluation, and detailed design. Each module consists of several procedures to be applied by the design team members in a flexible manner to identify new design knowledge through various means, generate and

explore new creative design concepts, evaluate the generated concepts and select the most suitable ones for further development.

The proposed work contributes much to the design development and creative design thinking through accomplishing several fundamental issues. Many creative tools and design knowledge representation were computationally developed, and integrated within a flexible, stimulating, and collaborative creative design environment to be used in various design disciplines. The system provides designers with highest manageability of their creative design environments and the hierarchical structure of design knowledge to suit their design problem situations and boundaries. Furthermore, the implementation of the proposed system as a web application enhanced collaboration through direct access to various design knowledge and achieved consistency in design knowledge reflected to all users.

The implemented case study has demonstrated many of the capabilities of the developed system in identifying new design data, representing design knowledge, generating new design alternatives, exploring various design options, and evaluating the generated and explored ones. It also has shown that the developed system has potential for enhancing the creative design thinking through exploration of more design ideas, collaboration, and new ways of design knowledge visualisation.

Considering future research, the present developed system has built a generic base in creative design environments which can be continuously developed and updated with new additional tools, techniques, and processes. The developed approach, through future research work, can be applied to other disciplines such as spatial design (architecture and interior), and e-learning.

ACKNOWLEDGEMENTS

Those who have supported me during this research are many and fill all the aspects of my life. They have offered invaluable support in the intellectual, emotional, economic, and spiritual realms of my life during this time.

My deepest appreciation and gratitude goes to Professor Hassan Abdalla, my supervisor and the Head of Product and Spatial Design department for his substantial faith, support, advice, guidance, patience, kindness, and friendship. He had confidence in my abilities to complete this research work when mine has faded. His wise supervision has made possible what I thought was not.

Thanks to Philadelphia University for providing me a scholarship to complete my research studies and to De Montfort University for the facilities and learning environment where I completed my research.

My personal thanks go to those who privately offered continuous support. To my dear parents and family who offered wisdom, support, belief and economic means and putting up with my struggles offering kind words and prayers. To my wonderful husband Hazem whose words of confidence, advice, patience, kindness, and love guided me through difficult times. To my lovely sons Ahmad and Shaker whose sweet words, support, and love lighted my life and gave me endless support and delight. They all deserve a major share of this degree and its potential benefits.

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NOMENCLATURE

SYMBOL

DEFINITION

AM	Alternative solution Module
APD	Active Projects Database
API	Active Projects Information
ART	Amplifying Representational Talkback
ASP	Active Server Pages
C	Computing
CACD	Computer Aided Conceptual Design
CAD	Computer Aided Design
CDS	Creative Design Situations
CDT	Creative Design Thinking
CG	Computer Graphics
CLR	Common Language Runtime
CPD	Collaborative Product Design
DODEs	Domain Oriented Design Environments
EME	Emergent Media Environment
FBS	Function Behaviour Structure
FSD	Fast Shape Design
GDK	General Design Knowledge
GM	Generator Module
GPI	General Project Information
HCI	Human Computer Interaction
H-creativity	Historical creativity

HTML	Hyper Text Markup Language
IAM-EMMA	Interactive Abductive Mechanism on an Environment for Multi Media Design
ICF	Issue-Concept-Form
ICT	Information Computer Technology
ID	Identification Document
IM	Interpreter Module
KBE	Knowledge Base Engineering
KID	Knowing-In-Design
LCM	Limited Commitment Mode
M	Modeling
OSD	Others Sample Designs
PC	Personal Computers
P-creativity	Psychological creativity
PM	Problem formulation Module
PPSD	Previous Projects Sample Designs
PSEs	Problem Solving Environments
RC	Requirements Capture
S	Sketching
SDK	Specific Design Knowledge
SOS	Subjective Objective System
SQL	Structured Query Language
TUIs	Tangible User Interfaces
UI	User Interface
URL	Uniform Resource Locator

W

Words

WWW

World Wide Web

WYSIWYG

What You See Is What You Get

XML

eXtensible Markup Language

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CHAPTER ONE

INTRODUCTION

1.1 Overview

Rapid growth in the consumer market, identification of urgent new technological advances, globalisation of the whole world, and the issues of environment, all these issues require the enhancement of designers' creativity to cope with this rapid growth and the attendant requirements.

Creative design thinking can be supported by providing the suitable means through developing creative design environments which incorporate the necessary elements for creative thinking using design computation. Such creative design environments require the investigation of various domains such as design, creativity, design computation, and collaboration in design. This research has presented a holistic approach in developing such computational design environments using advanced computer technologies to support creative design thinking among design teams.

This chapter provides a generic perspective of the rationale behind this research, its main aim and objectives, and its outcomes. Detailing of the rational of this research is discussed in section 1.2. Section 1.3 presents the research aim and objectives and how they were achieved. Furthermore, section 1.4 displays the research outcomes summarising the developed framework, the design computational model, the developed prototype system, the various features, and benefits of the developed system. Finally the thesis structure is outlined in section 1.5.

1.2 Rationalism

Creativity is considered to be a mysterious phenomenon. It can be defined as coming up with new, unique, and novel ideas. Two different debates were addressed: one considers creativity as a conditioned and inherited behaviour, a talent that only special people can have, while the second considers that every one exhibits analytical and creative talent to some extent and it is the job of the researchers to enhance it by providing the proper techniques and tools. Adoption of the second viewpoint requires defining the techniques and providing the proper tools to enhance creativity and become more competitive in the future consumer market. This also involves getting familiar with how creativity works and how it is evaluated, when and where.

Creative design thinking is an activity that involves the application and use of many creative tools to explore new solution spaces other than the already existing ones. These new solution spaces can be seen as an analogy of some existing solutions but in different domains. On the other hand they can be seen as combinations of several solution spaces from the same or various domains. Alterations or transformations are applied to make the solution spaces adequate with the design requirements and goals.

Various tools and techniques to enhance creative thinking are available. Many of these tools are applied in people's daily activities without even their recognition. Several ones are already used by designers to solve their design problems and help them explore new solutions. Through the last century such tools proved their ability to help creative thinking among people in various domains and particularly in design. Taking into consideration complexity in design, such creative tools need to be well structured and grouped to assist the design process in solving such complex design problems that may arise in the near future. This will assist design creativity and enhance competitiveness in this fast growing global market.

On the other hand, collaboration is one of the important issues in design. Many companies have their departments scattered at different locations in the world. New technological advancements provide the ability to communicate using the World Wide Web (www) to collaborate in solving design problems in large design companies. Providing these companies with specialized systems to assist their creative design process with the ability to communicate and share their ideas, comments and evaluations globally, is considered one of the necessities for such companies to minimize the lead time and be competitive.

Recent advancements in computer technologies can support research in design computation which is considered a more promising field recently. All previous research studies discussed specific areas but lacked the holistic view of design systems to support design teams throughout the design process.

Therefore, taking into consideration the previously mentioned issues, a holistic Creative Design Thinking (CDT) system is proposed to assist designers in their creative design thinking globally. The proposed system incorporates a set of creative thinking tools, design process modules including the various design stages, and relevant design knowledge databases. The CDT system provides a flexible design environment which can be adapted to solve problems in various design disciplines through the identification of relevant design knowledge from within its user interface.

1.3 Research Aims and Objectives

This research project aims to address the issue of creative thinking in design from a holistic perspective. Furthermore, to establish a new approach for applying evolutionary computing and visualizing technology in support of creative design thinking among design teams.

The objectives of this research are to investigate and develop various creative design techniques using design computation and new advancements in computer technology to

perception for designers, (6) the consideration of the various design processes from preparation to the detailed design and its integration with the suitable tools, and (7) the facilitation of design team collaboration through using the proper technologies and techniques.

To overcome the shortcomings in the investigated research studies described in CHAPTER TWO, a holistic approach to enhance creative design thinking through the various design phases is made possible. The developed framework comprises knowledge databases, a set of creative design tools, individual and team design environment, a user interface, and five design modules namely: preparation, concept generation, development, evaluation, and detailed design. Each module consists of several procedures to be applied by the design team members in a flexible manner. The developed framework supports designers to identify new design knowledge through various means, generate and explore new creative design concepts, evaluate the generated concepts and select the most suitable ones for further development. Flexibility was an important concern in developing the proposed system, since design process is considered a non-linear practice.

A computational model has been developed and presented in this research to form the basis for the developed prototype CDT system. The proposed framework requires a well structured design knowledge representation to be used by the incorporated creative tools, processes, and databases. Suitable design representation guarantees easy retrieval, update, and identification of new design knowledge effectively. Once the design knowledge representation has been structured, the creative tools computational methods can be implemented using this structured representation of design knowledge. Subsequently, the integration of these tools and knowledge representations with the design process modules can produce creative solutions through the interaction between the design team members and these integrated elements of the proposed computational system.

The developed prototype CDT system was designed taking into consideration efficiency, maintainability, reliability, non-linearity of the design process, and the previously defined

characteristics of a creativity support design environment. The design of the developed system was concerned about the enhancement of creative design thinking through various design stages. It provided users with an integrated, holistic, and flexible design environment which supports them not replaces them. It allows designers, through the user friendly interface, to identify new required design knowledge which can be updated, viewed and used by authorized design team members. Furthermore, it facilitates design knowledge visualisation using various visual representations such as data grids, tree views, and images. It incorporates the successful capability of representing the design knowledge hierarchically, storing it in the databases for later development, and utilising it by other creative tools to explore more options. Moreover, it has the capability of providing the design team with several creative tools to create design solutions and to explore more options based on these created solutions and the solutions already in existence. It comprises the facility to evaluate created design alternatives and store results at the various stages from abstract ideas to detailed ones. On the other hand, it has the capability to allow easy enforcement or release of constraints by the design team members as required through the user interface. It integrates various design stages with the suitable tools to support that stage and facilitate the design thinking process. Finally it has the facility of collaboration among design team members through the application of web-based technology to implement the proposed system.

The developed prototype system has been validated using a case study from the kitchen appliances industry. The case study has demonstrated many of the capabilities of the developed system in identifying new design data, representing design knowledge, generating new design alternatives, exploring various design options by using incorporated creative tools, and evaluating the created ideas. The implemented case study has shown that the CDT system has potential for enhancing the creative design thinking among design team members through exploration of more design ideas, collaboration, and new ways of design knowledge visualization.

Holistic approach to enhance creative design thinking through the conceptual design phase is made possible by developing supportive creative tools and techniques. The integration of various creative tools within a shared design environment facilitates collaboration among design team members to produce more creative ideas, evaluate them, and select the most appropriate ones to be developed and detailed for production. The early evaluation of design concepts minimizes the lead time for industry since the inappropriate ideas are eliminated early in the design process. Therefore, reductions in conflicts and inconsistencies at later design stages are achievable and the production of more creative ideas is viable.

The system has shown an innovative approach to integrate several factors which affect creative design thinking namely:

- Distributed design team members.
- Design knowledge representation.
- Creative thinking tools.
- Design processes.

The target user domain mainly includes design teams and design individuals whose creativity, efficiency and quick response to change are essential factors to their success and contribution in this global competitive market. Integrating creativity methods and tools within any design development can effectively assist designers through encouraging their design creativity and improving their overall performance. Most design industries can benefit from the proposed model by customizing it to their own requirements and needs. Simultaneously, it can be used in design education to enhance design students' creativity to cope with future markets.

The benefits which can be achieved from developing creative design environments are: more creative and competitive products, reduction in lead time to market, improvement in the design development processes and creative design thinking. By applying creativity methods, more creative and competitive designs can be produced to satisfy the market's

needs. On the other hand, lead time to market can be reduced by enhancing the design process through the application of computing technology and early evaluation techniques which can save time through the whole design and production phases. The improvement in the design development process is addressed by incorporating the creative design methods and tools within that process through the various stages of design for more creative results. These tools support the creative design process activities by providing designers with proper means to generate, explore, and evaluate alternatives through the different stages of design.

1.5 Thesis Structure

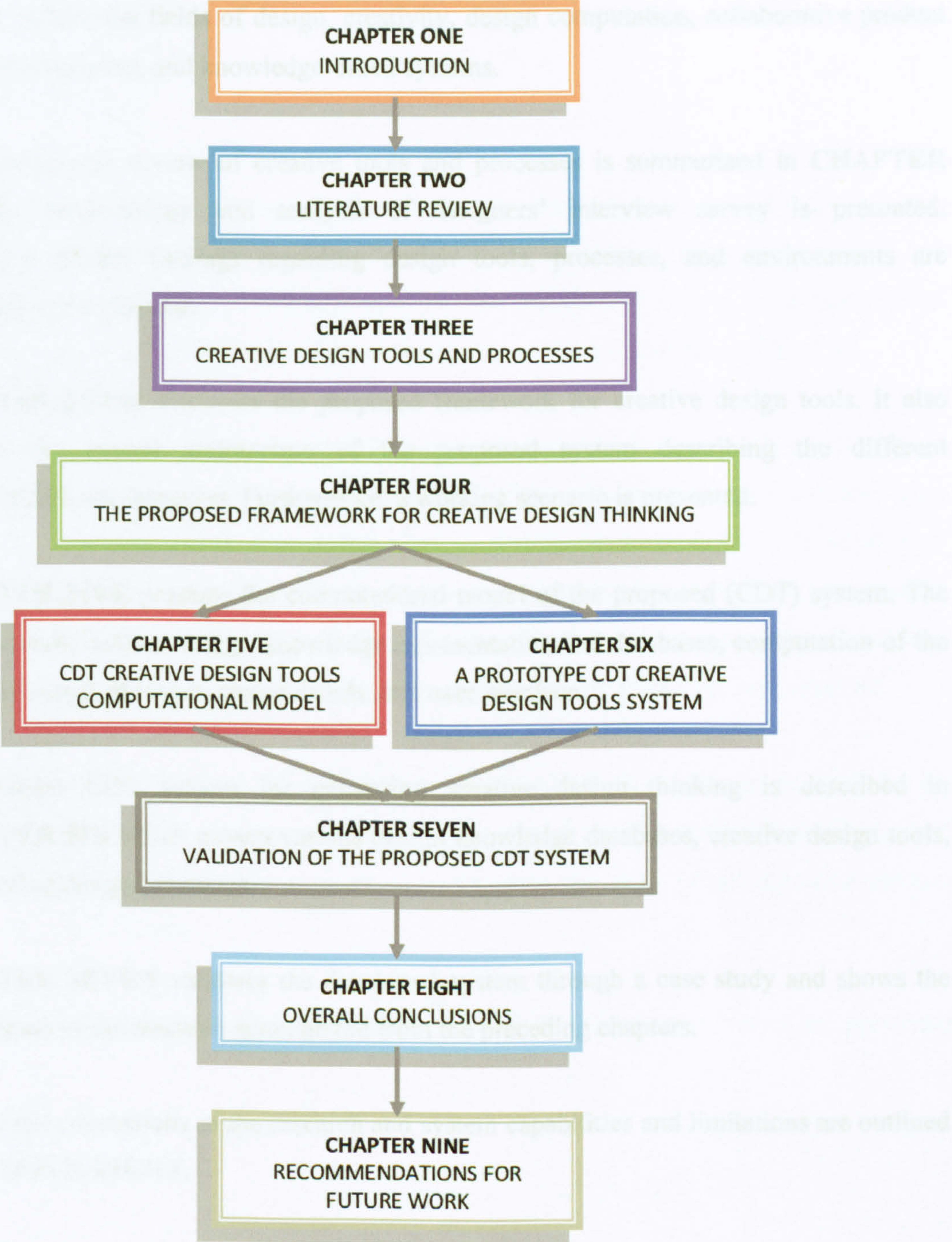


Figure 1.1 Thesis structure

1.5 Thesis Structure

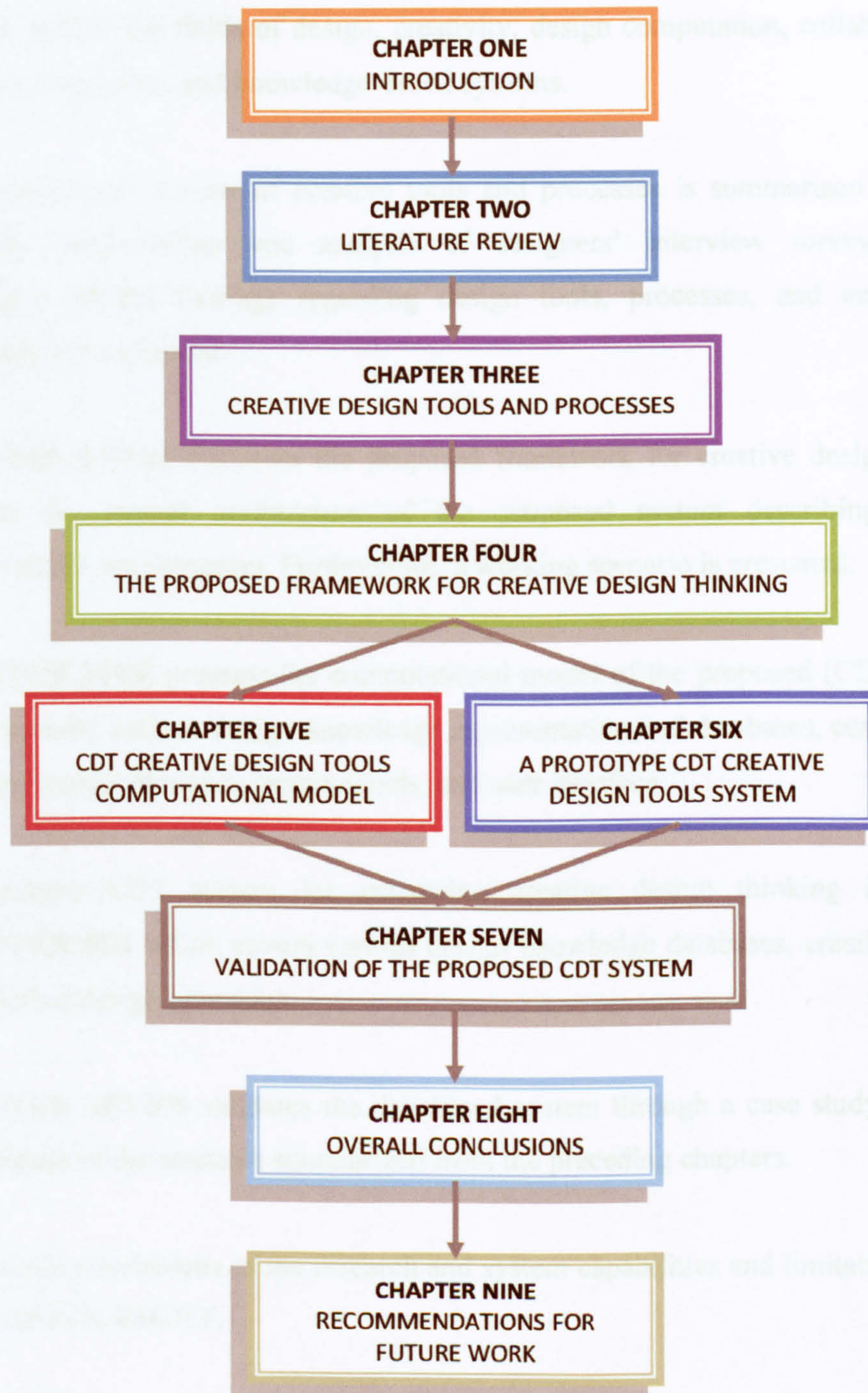


Figure 1.1 Thesis structure

The structure of this thesis is organized over nine chapters as shown in figure 1.1. **CHAPTER TWO** comprises a comprehensive survey of relevant literature. The subjects covered include the fields of design, creativity, design computation, collaborative product design development, and knowledge-based systems.

A comprehensive review of creative tools and processes is summarized in **CHAPTER THREE**. Methodology and analysis of designers' interview survey is presented. Discussion of the findings regarding design tools, processes, and environments are addressed and explained.

CHAPTER FOUR discusses the proposed framework for creative design tools. It also presents the overall architecture of the proposed system describing the different components it encompasses. Furthermore, a working scenario is presented.

CHAPTER FIVE presents the computational model of the proposed (CDT) system. The issues covered include design knowledge representation and databases, computation of the proposed design modules, creative tools, and user interface.

A prototype CDT system for enhancing creative design thinking is described in **CHAPTER SIX** which covers various design knowledge databases, creative design tools, and creative design processes.

CHAPTER SEVEN validates the developed system through a case study and shows the significance of the research summarized from the preceding chapters.

The overall conclusions of the research and system capabilities and limitations are outlined in **CHAPTER EIGHT**.

Finally, recommendations for future work are presented in **CHAPTER NINE**.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

Several research academic areas related to this current research are reviewed in this chapter. The covered areas in the literature survey are design, creativity, design computation, and collaborative product design and development. The outcome of the survey is summarized and several conclusions are drawn. The chapter's structure is illustrated in figure 2.1.

Section 2.2 explores the area of design. It reviews the relevant developments that have been accomplished in the nature of design, design thinking, conceptual design and sketching, design processes, and Computer Aided Design (CAD). In section 2.3 a description of creativity and reviews of research work in the area concerning nature of creativity, creative thinking models and tools, and creativity in design which includes creative design process, creative design models and support tools, and creative design evaluation are presented.

Section 2.4 reviews the area of design computation and outlines several frameworks for various systems in the area of situated design, visual design, artificial creativity and evolutionary design. Furthermore section 2.5 discusses the issue of collaborative product design and development.

Finally a critical appraisal of previous research and scope of the present work are presented in section 2.6.

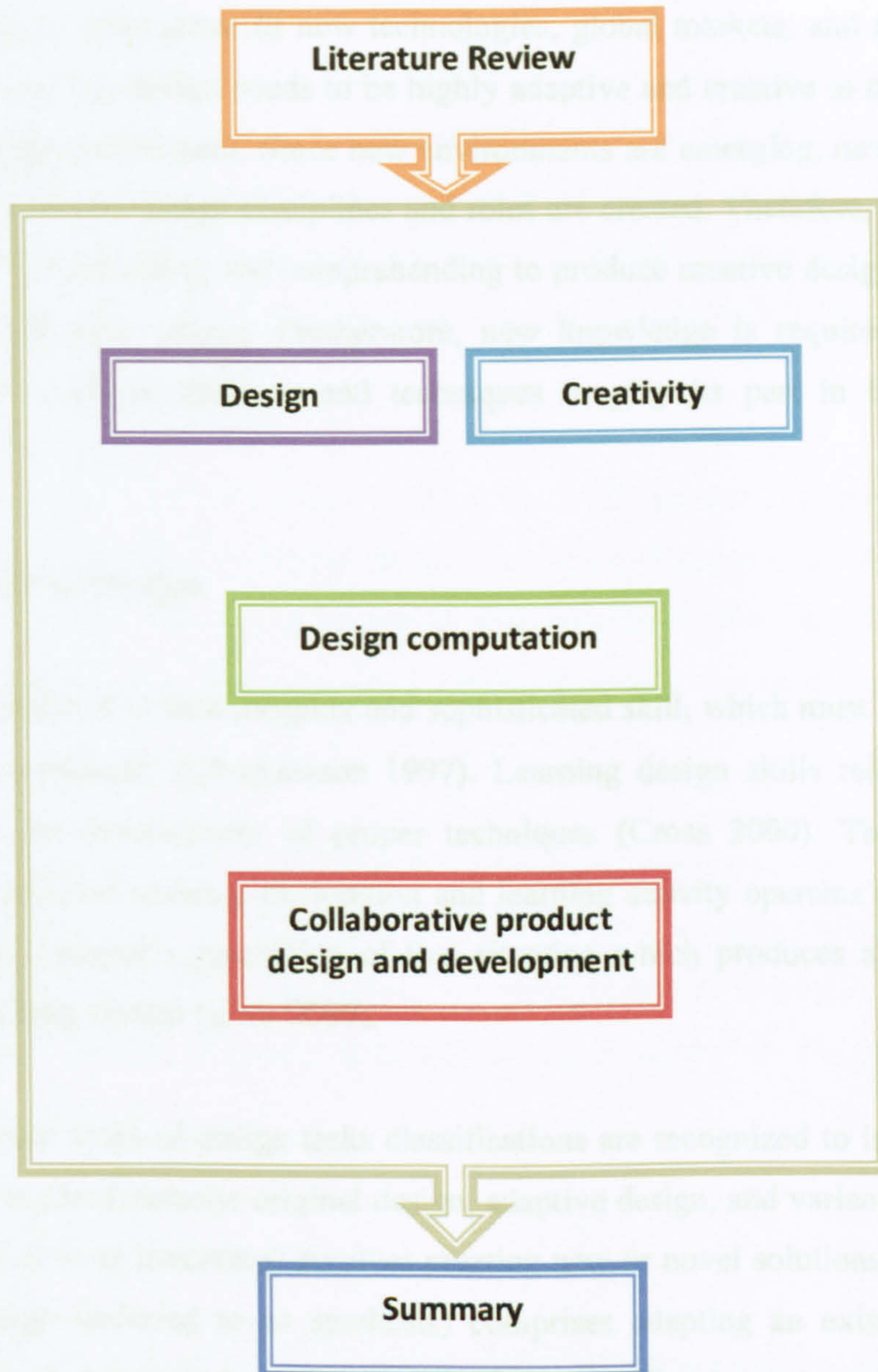


Figure 2.1 Structure and Layout of the literature Review

2.2 Design

Recently with the emergence of new technologies, global markets, and new pressures on business and society, design needs to be highly adaptive and creative to meet the demands of this changing environment. Since new environments are emerging, new design contexts are required, and new design disciplines and roles are created. Therefore, design requires a great deal of understanding and comprehending to produce creative designs in competitive time within this new setting. Furthermore, new knowledge is required to support the development of design methods and techniques to play its part in this fast growing situation.

2.2.1 Nature of Design

Design is considered to be a complex and sophisticated skill, which must be learnt like any other sport or musical skill (Lawson 1997). Learning design skills relies on controlled practice and the development of proper techniques (Cross 2000). This goal oriented, constrained, decision making, exploration and learning activity operates within a situation related to the designer's perception of that situation which produces a description of a future engineering system (Gero 2000).

Several different ways of design tasks classifications are recognized to indicate the extent of the effort required namely: original design, adaptive design, and variant design. Original design (referred to as inventing) involves creating new or novel solutions for a given task. Adaptive design (referred to as synthesis) comprises adapting an existing system to a different task or developing a momentous subsystem of a current product. It embraces novelty with no massive restructuring of the system. The majority of design tasks are within this classification. On the other hand, variant design (referred to as modification) embraces transforming the parameters of certain features of a product to develop a new

more substantial design, such as size, material properties, and colour to mention a few (Otto and Wood 2001).

Two different design classes are acknowledged, routine design and non-routine design (Gero 2000). Routine designing is a familiar design where the necessary knowledge is available and can be solved using a well-known procedure. On the other hand non-routine designing is a creative or innovative design where the necessary knowledge is not available and the designer does not have a well-known solution procedure, therefore a new procedure must be generated (Visser 1996).

Engineering design is a process which involves the establishment of requirements based on human needs, which will be followed by transformation of those needs into specifications and functions, which in turn are mapped and converted into design solutions using creativity, scientific principles and technical knowledge to be cost-effectively manufactured (Liu et al. 2004).

Studies in the literature review discussed the definition of design where it was accepted that design is considered a complex learnt skill which involves goal-oriented, constrained, decision making and exploration within a certain situation. It requires an appropriate development of methods and techniques, taking into consideration the given requirements and goals to be achieved.

2.2.2 Design Thinking

Understanding how designers think is a great challenge to researchers in the design field. In order to understand designers thinking researchers must expand their knowledge of human cognitive processes since design is considered to have a strong resemblance to the field of cognition by considering it one of the most significant of intelligent behaviours in humans. Visual perception, action, language, memory, and reasoning all are cognitive processes which are essential to all human intelligent activities as well as design processes. It is also

necessary to develop a better understanding of the nature of design and the characteristics of design problems and their solutions as Lawson (1997) mentioned.

Visual perception is an essential part in design thinking. Applying knowledge to design situations is always based on the way designers' interpret what they see. Therefore, it constitutes a major part in design styling, and its attractiveness to users. Two stages of visual processing were addressed; pre-attentive, and attentive (Baxter 2002). Pre-attentive is a very rapid process where the overall design is scanned to seek explicit patterns and shapes, usually no deliberate effort is required from the viewer. On the other hand, attentive processing requires deliberate focusing and searching for details of the design or image to figure its implicit component parts.

An empirical study on both experienced and inexperienced designers was conducted by Liu (1995) to reveal the importance of seeing shapes and the variables embedded in design visual perception. Four phenomena of design visual perception were addressed. The first was that experienced and inexperienced designers managed to recognize explicit shapes. However, only experienced group managed to recognize implicit shapes. The second was that explicit, closed, and nameable shapes are the first to emerge in the seeing process. The third indicated that the time required to locate emergent sub shapes is proportional to the complexity of that shape. Finally, experienced designers managed to lower their thresholds of recognizing activation to be able to uncover implicit shapes; this was due to their experience and training.

Various representations are used in developing design ideas such as sketches, images, words, annotations, models and many more. Using word graphs or annotations in design thinking was discussed by Segers et al. (2005). The study discussed the effects of providing feedback to the designers' annotation using word graphs based on those annotations and semantic associations. It was recognized that there was an improvement in the work flow with more associations, in addition to the appreciation and pleasure it gave to the designers. Nevertheless, no evidence of creativity enhancement or reduction of fixation was addressed.

The importance of narrative and memory in design thinking was addressed by Lawson (2004) through the studying of designers' conversations. It was recognized that these conversations were full of references which lead to huge chunks of information. Furthermore, it drew the attention to the importance of words and pictures in the design thinking process. It was evident that experienced teams use a shared language and have many common expectations. Furthermore, he pointed that design knowledge is more dependent on experiential memory than any other profession. Experts not only gain more experience but they link problems to solutions through recognition of design situations and seeing of underlying or implicit patterns.

Reasoning is considered an important feature of human intelligence, which is frequently used in design thinking. It is the ability to retract previous knowledge whenever a similar situation occurs. There are several approaches of reasoning to be applied in any design process, for example functional reasoning, case based reasoning, or analogical reasoning.

Functional reasoning is mainly conducted at the functional level so as to produce solutions for certain design problems. Various functional reasoning approaches were addressed, each has a different methodology. Chakrabarti and Bligh (2001) discussed three existing approaches and criticized them before proposing a new approach to overcome observed shortcomings of: Freeman and Newell's model, paradigm model, and the systematic model. Three requirements for the ideal functional reasoning approach were defined. The first is the ability to support designs of any nature either routine or non-routine designs. The second is the ability to support designing at any level. The third is the ability to support evolution of designs through levels of detail. None of the three discussed approaches satisfied the three requirements altogether or supported innovative designs. Each one of them satisfied just one of those requirements. The proposed functional reasoning approach was based on the combination of a set of known ideas, solutions, or structures in all possible ways to generate multiple solutions or concepts. In order to produce innovative solutions the known solutions should be basic and their rules of combination should be more comprehensive (Chakrabarti and Bligh 2001).

Analogical reasoning is considered a special case of case based reasoning. Two differences were clarified between these two types of reasoning. The first concerns the relationship between the target and source which is used to retrieve data from a source. In analogical reasoning the relationship is the similarity between the two, while, in case based reasoning it is the usefulness. The second difference concerns the mechanisms and strategies used to retrieve the data from the source. It is supposed that the same mechanisms are used to access a source independently of its distance to the target, although it is more difficult to establish analogies between target and source with distant knowledge. This in return can produce surface analogies rather than deeper structural ones (Visser 1996).

Many design thinking models were established and addressed in the literature. Simon (1981) modelled design as a search from an initial state through many intermediate states to reach the goal state. Designers move through the search space from one state to another by using procedural knowledge. Conversely, Schon and Wiggins (1992) proposed the seeing-moving-seeing design model. Designers see the representation, draw new ways in relation to it and then see the new representation. Liu (1996) described designing differently; it is neither a general search as Simon (1981) model nor seeing- moving cycles as Schon and Wiggins (1992) stated. Liu (1996) grouped the two design models in what he called two-search model of designing. His combination search model included shape restructuring search and knowledge transforming search.

On the other hand, Lawson (1984) compared the approaches in which designers and scientists solved the same problem. The study concluded that scientists solve problems using analysis and 'problem-focused strategies' while designers use synthesis and 'solution-focused strategies'. Alternatively Cross (2000) showed that systematic design approach can be helpful to designers in solving their design problems. Consequently he proposed a design process which includes clarification of requirements, search for information, use of first solutions to clarify the problem, avoiding fixation at early stages, and producing variable solutions with periodical assessment and evaluation.

Premature commitment to a specific design solution is known as fixation in design. Designers sometimes get trapped by features of a certain proposed design solution or an existing previous one. This important issue was discussed by various researchers taking into consideration its effect in hindering the production of innovative and creative design solutions. Two studies by Jansson and Smith (1991) and Purcell and Gero (1996) tackled this fixation issue empirically. Some contradictions were recognized between the two study results.

Jansson and Smith (1991) argued that showing designers a prospective example solution of the given design problem former to a design session should result in design fixation. Their study involved three different types of design problem which were given to advanced undergraduate and practising mechanical engineers to solve. The control group was simply given a requirement of the problem, while the other groups were given the same requirement accompanied by a picture of a possible solution. They proved that showing designers an image of a potential design solution to a problem prior to a design process results in fixation.

On the other hand, Purcell and Gero (1996) referred to the results reached by Jansson and Smith (1991) as being associated with the absence of domain specific knowledge and a reliance on everyday knowledge activated by exposure to a picture of a familiar example. Therefore, they studied the issue of design fixation further using various design disciplines and several different approaches. They discussed the effect of verbal descriptions of possible solutions in addition to pictorial representations. In the discipline they chose for the study (industrial designers) no fixation were addressed in both cases, which contradict the previous study.

They conducted more experiments with industrial and mechanical engineers to have similar disciplines as the study of Jansson and Smith (1991). Fixation was recorded among mechanical engineers while no fixation was recognized among industrial designers. Additionally, more alternatives were produced by industrial designers. This could indicate

the differences in educational approaches in the two disciplines where there is more focus on innovation in the industrial discipline. Furthermore, in another experiment Purcell and Gero (1996) presented designers from the same two design disciplines with innovative pictorial representation prior to the design session. It was noticed that fixation on the presented principle occurred among mechanical engineers who tried to explore new ways of solving the problem using this principle. Conversely, no fixation was noticed among industrial designers and no evidence of producing innovative design using the presented principle. Purcell and Gero (1996) concluded that industrial designers got fixated in being different rather than being fixated in some design solutions.

Human cognitive processes are essential substances to human intelligent activities and design thinking processes. They either support or hinder the design process. All design models described in the literature lacked the tools or techniques to enhance the design thinking process. Furthermore knowledge is a major part in such situations. Experience is a source of knowledge for designers, but is not enough to search for new analogy or case based reasoning. More structured knowledge is required to support the design tasks.

A particular shortcoming of the previous research works on design fixation was that the pictorial representations shown to the designers prior to the design session were from the same problem domain. No other representations from other domains which can be related to the design problem were represented or studied. This issue could be an important factor in minimizing design fixation. By broadening the search area for designers in other domains; it is possible to find analogical emergent innovative solutions to the design problem.

2.2.3 Design Process

It is very reasonable to argue that for design to take place a number of processes must occur. These processes may vary among designers in their nature and even in their

sequence. Various models of design methods and processes were proposed by many researchers.

Hubka (1982) proposed a design framework based on functional views of the design problem. The proposed steps were to establish function structure, establish technical process, apply technical systems and establish boundaries, establish groupings of functions, establish functional structure and represent it, establish inputs and modes of action, establish classes of function carriers, combine function carriers and examine relationships, and finally establish arrangements.

Another process composed of seven stages was proposed by Pahl and Beits (1988). The process starts by identifying essential problems which will be followed by establishing function structures, and then the search for solution principles takes place. Combination of solution principles is conducted before the selection of the suitable ones. The selected ones are then firmed into concept variants and evaluated against technical and economic criteria.

Exploring the design situation was the initial step in Jones (1992) model. Then the problem structure is perceived and transformed, boundaries located, sub-solutions described and conflicts identified. Afterwards sub-solutions are combined into alternative designs, evaluated and final design is selected.

Furthermore, Cross (2000) developed a design process which is initiated by clarifying design objectives followed by establishing functions, setting requirements, and determining characteristics. Afterwards the generation of alternatives takes place followed by evaluation of the generated alternatives and then improvements of the selected options.

Crawfer and Di Benedetto (2006) recognized the role of design in the new product development process. They identified the contributions of design to that process and classified them into six categories namely: design for speed to market, design for ease of manufacture, design for differentiation, design to meet customer needs, design to build or

support corporate identity, and design for the environment. Furthermore, they highlighted the purposes of design which were aesthetics, ergonomics, function, manufacturability, servicing, and disassembly.

Lawson (1997) argued that design is a negotiation between problem and solution through the three activities of *analysis*, *synthesis* and *evaluation*. The design process is endless with no perfectly correct process; it involves finding as well as solving, and subjective value judgement. It is a prescriptive activity where designers work in a context or a need for action. Some methods were proposed such as: understanding the problem, scenario, generating alternatives, and parallel lines of thoughts.

Cross (2000) classified design methods into two major groups; *creative methods* to stimulate creative thinking by increasing the flow of ideas, removing the mental blocks that inhibit creativity, and widening the search area, *rational methods* which encourage a systematic approach to design. These processes complement each other to reach a systematic approach. Furthermore, he indicated that some design methods are new inventions of rational procedures, some are adapted from operational research or any other source, while some other are formalization of the informal techniques already used by designers.

Requirements Capture (RC) is at the front end of the design process in any new product development. It is the process of research and identification of the needs, preferences and requirements of individuals or groups related to the design problem such as clients and stakeholders. It identifies customer, user and market requirements, design requirements, and technical requirements. It is necessary to conduct a thorough RC to avoid false assumptions of those requirements (Bruce and Cooper 2000). Three different phases of RC model were presented; information gathering, information transformation, and requirements generation.

Furthermore, Darlington and Culley (2004) investigated design requirements capture through conducting a series of case studies in three engineering companies. They recognized that the RC activity in the considered case studies was a responsive ad hoc approach. Two principal roles of the design requirements were addressed; firstly they serve as an agreement about the end product, and secondly they provide a basis on which the designer can build his design solution and synthesis. Several factors were identified that can influence the design requirements' content such as politics and social context in which they take place.

In another study Ziz-Av and Reich (2005) proposed a Subjective Objective System (SOS) which addressed the mapping from customer requirements to a product concept considering different design issues. The method was based on four mathematical descriptions: objective and subjective components, varying degrees of precision in modelling, decomposing a complex problem into sub-problems, and highly simplified evaluations.

It is noticeable that the displayed frameworks and processes all are detailed under a general process of design which includes the preparation stage before concept generation which is followed by evaluation and selection of the most promising options. However, only Pahl and Beits (1988) managed to include the identification of essential problems as the first step of the design process, and only Cross (2000) included clarifying objectives. These important steps of problem identification and defining objectives are essential ones in creative design thinking where problem identification plays a vital role in the creative process.

2.2.4 Conceptual Design and Sketching

Conceptual design is one of the early stages in the design process that demands the greatest creativity. Its main aim is to produce design principles concerning the product form and function to satisfy customers' requirements and be competent. Lots of concepts are usually

generated at this stage, followed by the selection of the best promising alternatives (Baxter 2002).

Two main steps are identified in conceptual design; divergence and convergence. Generation of concepts is known as the divergent step while the evaluation and selection of concepts is known as convergent step. The main aim of the divergent step is to widen the search for new ideas while the convergent step is supposed to decrease the number of concepts to be developed according to the evaluation criteria and selection (Pugh 1991; Cross 1994). Generally design process follows multiple divergent convergent steps which are adopted after sketches or visualization of concepts took place.

Liu et al. (2003) discussed different types of divergence-convergence approaches. The first was the use of series of divergence without convergence until sketches are generated. In design computational environments, this approach results in a very large conceptual space to be explored manually. The second approach was the use of multiple divergence convergence that is conducted in each level of solution abstraction. This will produce reasonable numbers of concepts at each level followed by screening and selecting of these concepts. At the second approach the result solution space is believed to be manageable but the solutions are represented at an abstract level to be comprehended. Therefore they suggested an ideal approach for conceptual design which follows multiple divergence convergence to increase gradually the number of generated concepts to reach a level beyond abstraction so that they will be understood by designers. Thereafter a divergent and convergent approach tends to detail these concepts and decrease the solution space. As the researchers claimed, this approach should be more efficient than the single divergent step because it reduces the number of abstract concepts to be considered without any compromise in the solution space.

At this early stage of the design process, designers from various disciplines need to collaborate to create optimal solutions that reduce the need for elaboration in later stages of the design process. It will be beneficial to develop a design working environment that

enhances creative and innovative interdisciplinary design among design groups. Lack in synchronization between team members results in miscommunication and uncoordinated actions. Therefore, MacMillan et al. (2001) addressed this issue and suggested that for interdisciplinary design teams to work together efficiently and in synchronization, an integrated design framework is required. Such models need to be flexible to comply with the dynamic nature of the design process and achieve interdisciplinary interaction between various processes of design such as the technical, the cognitive and the social process.

Such a framework was proposed by MacMillan et al. (2001) and was validated by Austin et al. (2001) (phase and activity model). The suggested model encompasses two main stages. The first stage is to develop the business need into design strategy by interpreting the business needs, functional requirements, and essential problems, followed by developing the functional requirements, key requirements, and project characteristics. The second stage is to develop design strategy into concept proposals through divergence, transformation and convergence steps. The divergence step is to search for solution principles, the transformation is to transform and combine solution principles, select suitable combinations, and then firm up into concept variants. The final step of convergence is to evaluate and choose alternatives, and improve the details and cost options. When the design teams followed this design process as suggested by Austin et al. (2001) it was recognized that their performance as a team was better.

Visualization can facilitate the concept generation in any design process. Two types of visualization are distinguished; memory visualization and imagination visualization. Memory visualization utilizes the images and representations held in ones mind from previous experience. On the other hand, in imagination visualization, a creation of a new event is structured instead of recalling a past experience from the memory. Therefore, the use of each type of visualization influences the development of design concepts (Dahl et al. 2001). Furthermore, a conceptual framework that links the two types of visualisation and the incorporation of the end user to the nature of the design process and outcome such as originality, usefulness and customer appeal was discussed. It was recognized that the use of

imagination visualisation produced more original designs. Given that designers usually use memory visualization; the use of imaginative visualization and the incorporation of the end user were not automatic tasks in the concept design visualization. Designers need to be encouraged to do so.

Verstijnen et al. (1998) and Van Der Lugt (2005) studied the sketching behaviour and functions. The results assured that sketches can stimulate creative design thinking by providing new directions for idea generation and providing a more integrated group process by facilitating better access to the earlier ideas.

Won (2001) discussed the cognitive visual thinking of designers and design representations using conventional and computers media at the concept stage. The hypothesis was that the visual thinking of designers using both types of media will be different. The study concluded that the use of computer will stimulate the designer to generate ideas strongly and more frequently because the designer will be influenced to create some images in his/her mind from the immediate visual feedback of the computers. Similarly, the attention of the designer will shift from the 'total' of the sketch, with more frequent shifting time that stands longer than in the traditional way.

In the conceptual design stage designers go through iterative action/reflection cycle. The designers externalize their ideas using sketching or other ways of representations such as diagrams, or documents using computers. The results are represented back to the designers where they will be inspired to generate new ideas or concepts (Hoeben and Stappers 2005). This view is referred to as representational talkback in Nakakoji et al. (1998). This representational talkback will result in enhancement of the design concepts both internally inside the designer's mind, and externally such as computer drawings and documents.

Hoeben and Stappers (2005) presented some tools from the literature that implements the talkback in various design domains. One tool named Amplifying Representational Talkback (ART) implemented representational talkback for documents; it lacked graphical

representations to be used in design. Another tool (The electronic cocktail napkin) was aimed at architectural plan sketching. It recognizes formalized sketch strokes and provides the user with the option of displaying the raw strokes or the interpreted ones. Some other tool is DENIM for designing websites and laying out web pages. It does little recognition of user's input and deals with more formalized matters than the compound sketch. The final tool presented was (Teddy) which is a 3D modeller for organic shapes. It interprets drawing strokes in a way close to the designers' sketches. This makes the designer focuses on the ideas behind the sketches not the good looking images. As a result of this literature review Hoeben and Stappers (2005) developed a digital sketchbook tool for sketching. Their tool focused on two functionalities; sketching and browsing of the drawn sketches. It facilitates sketching without any understanding or interpretation of those sketches. This tool is like a personal sketch book which the designer can put in his concepts and get back to them later whenever needed. It lacks any useful connections with knowledge of design or other tools to support the design process.

Furthermore, various functions of sketching were addressed in the literature and discussed by Van Der Lugt (2005). The discussed functions namely: thinking sketch, talking sketch, and storing sketch were used to assess idea generating meetings. A model that considers sketching functions as interactions between the team members and their external memory was proposed and validated. Three link types were categorized; exchanges between the designer and his/her individual direct external memory refer to thinking sketch, exchanges between the designer and the shared direct external memory reflect the talking sketch, and finally exchanges with the individual and shared remote external memory refer to the storing sketch. It was concluded that the thinking sketch and the storing sketch support creative process in design teams.

Two types of transformations between sketches in the early design stages are lateral transformations, and vertical transformations. Lateral transformations express the movement from one idea to another different one. Vertical transformations represent the movement from one idea to a detailed version of the same idea (Rodgers et al. 2000). It was

recognized that a balance between lateral transformations and vertical transformations is necessary to produce good design. At the later stages of design development where more details are required, vertical transformations dominate.

On the other hand, the impact of digital technology on conceptual tools and sketching was investigated by Jonson (2005). Four categories of conceptual tools were discussed: sketching (S), words (W), modelling (M), and computing (C). Free hand sketching with annotations was marked as sketching (S). Spoken and written words, plus internet searches were marked as words (W). Furthermore, modelling was referred to as any activity that involves direct manipulation for example of material. On the other hand any digital work such as CAD was described as computing. Verbalisation using words emerged to be the major conceptual tool for getting started and it highlighted the social and collaborative features of design. Furthermore, the combination of tools suggested that design concept generation was an interaction between visualisation and verbal tools.

Although sketching using conventional media can produce immediate speed sketches easily with high expressive qualities and no constraints except for the designer's imagination, still computers can provide other advantages which can be more useful and desirable in some design cases. Using computer sketching tools can provide storage facilities, faster search for information held in storage via a certain criteria, durability, and direct link to other computer tools and networks (McGown et al. 1998).

Computational environments which use drawings as an interface to knowledge-based systems were addressed by Do (2005). He developed a right-tool-right-time framework which used computational tools to recognize free hand sketching symbols and based on this recognition relevant design tools are activated such as: 3D CAD geometric modelling program, mathematical calculator, and Archie Case-Based Design Aid. The conceptual model of the right-tool-right-time environment has a process flow of several stages: (1) drawing symbols and configurations, (2) contexts identification, (3) intention recognizer, (4) inter-application communicator, and (5) design tools. The symbols and configurations

are mostly basic design elements combined with specific spatial relations. More ways can be derived and searched to use drawings as interfaces which are programmed to access different type of systems and applications.

Conceptual design is a major part in the design process where most of the creative illuminations are discovered. It involves several iterations of divergent-convergent steps to reach creative suitable solutions. It was noticed that there were few studies that focused on the design procedures in order to support and enhance the generation of more creative design solutions. Furthermore, visualising of design alternatives and its related knowledge plays a vital role in the creative process at this early stage. Drawing is believed to be a way of externalizing the designer's thoughts and ideas either using computers or conventional medias. Conventional media used to be the only way of drawing before the CAD tools were created. Conventional ways are still preferred by some designers for sketching in the conceptual design stage. While CAD tools are used for the final design stages when more detailed accurate drawings are required. It is recognized that different types of drawings are used within various design processes. Sketching and diagramming in the early conceptual stages was tackled and discussed by many researchers from different view points to study its function during the design process, the cognitive processes it involves, and to pinpoint its vital role in that design stage.

2.2.5 Computer Aided Design (CAD)

The process of developing pictorial and diagrammatic representations is an essential part of the design process to develop design solutions (Purcell and Gero 1998). In the literature several researchers studied the role of drawing in design; several attempts have been made to develop computer aided concept design apart from commercial software providers to overcome the shortcomings of CAD tools in the early stages of design.

Van Dijk (1995) developed a Fast Shape Design (FSD) prototype which is a new CAD system. It provided tools for designers similar to conventional 2D sketching. He used input devices that mimic the hand movements. Therefore it was not supposed to replace traditional sketching but instead use it for 3D modelling.

Another study by Van Elsas and Vergeest (1998) discussed the shortcomings of Computer Aided Design (CAD) tools in the conceptual design stage over Computer Aided Conceptual Design (CACD). They proposed a method for design of displacement features in the conceptual design stage. It allowed designers to create detail features from an existing surface by relocating a certain controlled portion of it. Although the tool had various shortcomings such as the lack of possibility to model more than one feature on the same surface and the impossibility of overlapping features, it was considered very useful for conceptual design, easy to use, and provided enough freedom to shape with the given parameters.

Furthermore, Tovey and Owen (2000) described two methods for producing concept models based on sketches. Direct modelling from the concept sketches to produce 3D computer models and sketch-mapping by attaching concept sketches to simple CAD models to produce 3D sketches. It was recognized that the use of direct modelling in the early divergent stages of conceptual design inhibits the creation of more alternatives which is the main aim of this early stage of design. Therefore, they developed the sketch mapping tool which includes the advantages of conventional sketching tools and the rapid production of animated 3D CAD models. They concluded that a combination of both methods can provide the optimum design process.

The DART system developed by Chapman and Pinfold (1999) tried to overcome some of the limitations of CAD systems in the data analysis process. Knowledge Based Engineering (KBE) was used to develop the concept tool. In their system the designed model can transform itself automatically depending on the process required at that stage. This was achieved based on the object-oriented representation of the design process. This allows

designers to use the generated model and perform a series of analysis which will allow more numbers of alternatives to be considered.

The previously mentioned systems concentrated on design modelling in the early design stage. Some other systems were approached differently. Dong and Agogino (1998) developed an information sharing system based on smart drawings, where the CAD drawings can be linked to other informational documents such as memos, spreadsheets, and analytical results. The linked documents can be accessed by clicking on the graphical entity, and they can be edited or viewed. One of the benefits of this system is that it does not require standardized data structures like conventional approaches. The design data are distributed and not unified.

Moreover, Meniru et al. (2003) discussed the absence of computer support in conceptual building design. They investigated how designers work during the conceptual phase with concentration on the manipulation and organization of information. Specifications for the creation of a computer tool to support this early stage of design were proposed. The specifications covered various design tasks involving the conceptual design stage namely: requirements repository, application of requirements, multiple levels of abstraction, version management, element interaction, automatic feedback, design overview, and design liability.

Sener and Wormald (2008) addressed the shortcomings of existing computer-aided design CAD systems used by industrial designers which do not suit their needs for designing product forms. The study noted that the combination of sketching and constrained form design was desirable by designers but is still elusive in currently available systems. In order to maximise usefulness in manufacturing and analysis applications, they claimed that replacement systems should be based on surface modelling technology. Their research pinpointed that such systems' users favour Human Computer Interaction (HCI) that provides naturalistic, spontaneous and expressive tools for form sketching. Furthermore, users were recognized to favour customisable and intelligent design environments.

Although various research studies tackled the issue of CAD tools in design, still more is required to support the early conceptual design phase where a lot of vague ideas and abstract design knowledge are available. In order to use CAD tools, precise information regarding the structural geometry of the product is required which does not support the creative aspect of conceptual design. Designers need a tool which they can use spontaneously to sketch their ideas quickly without wasting their time on thinking of such details and forgetting about the main theme of the concept. Furthermore, it can be useful if their sketches can be linked with related design knowledge which can support their ideas and facilitate visualisation of their concepts.

2.3 Creativity

In this section several issues of creativity are discussed in detail. The nature of creative thinking in general from psychological and design views is described. Then a display of various models and tools of creativity are presented which is followed by a discussion about creativity in design demonstrating the various techniques and tools applied to enhance creative design thinking. The last part talks about creativity measurement and evaluation.

2.3.1 The nature of creativity

Three perspectives on creativity were introduced from the literature, inspirationalist, structuralist, and situationalist (Shneiderman 2000). Inspirationalist writers believe that moment of illumination can be reached through preparation and incubation. According to them the creative process starts with problem formulation and ends with evaluation and refinement. They encouraged the vision of creativity as being 1% inspiration and 99% perspiration. Therefore, any moment of insight should be followed by loads of hard work to reach creative useful solutions. They usually support the use of brainstorming techniques,

free association, lateral thinking, and divergence. Furthermore, they are always oriented to visual presentation techniques to externalize relationships and solutions. Structuralist writers emphasize on studying previous work and using systematic methods to explore the solution space. They are oriented toward visual presentation as well but to present structured diagrams, decision trees and flow charts. On the other hand situationalist writers think of the social and intellectual context as a major part of the creative process. They usually support accessibility to previous work, consultation with other team members in the field, and dissemination of solutions to other team members.

Boden (1994, p.75) stated that: *“Creativity is a puzzle, a paradox, some say a mystery. Inventors, scientists, and artists rarely know how their original ideas arise. They mention intuition, but cannot say how it works. Most psychologists cannot tell us much about it, either”*. Two senses of creativity were differentiated psychological (P-creativity) if the idea is new to the individual who created it no matter how many times other people have already had the same idea, and historical (H-creativity) if the idea is P-creative and no one else, in all human history, has ever had it before.

The study of creativity is interdisciplinary. It has been rooted in psychology, epistemology and sociology (Gardner 1994). Two broad definitions of creativity were reviewed: one emphasizes creative thinking and promotes that creativity can be studied solely as a mental phenomenon; the other recognizes that creativity goes beyond the generation of novel ideas since society plays an important role in defining what is creative.

Three types of creativity are distinguished according to the process used in generating the creative ideas namely: combinational, exploratory and transformational (Boden 2007). The combinational creativity involves the creation of an unfamiliar idea from existing familiar ones. Exploratory creativity makes use of the existing rules to create new ideas or structures. While in transformational creativity new rules are added and some of the old ones are dropped. According to Boden (2007) various ways are relevant to encourage creativity depending on the type of it. For combinational type, widening the general

knowledge, experimenting unfamiliar combinations, and learning how to evaluate the generated outcomes to pick the proper ones are the proposed ways. Regarding exploratory type, it needs experience of the related thinking style above the previously mentioned ways. As for transformational type it requires seeing examples of transformation and be able to evaluate the results as well.

According to Ward et al. (1995) abstraction is vital to the creative process. Using old information and expressing it in an abstract form can help in developing new ideas. It helps to identify the goals of the problem to be solved. To meet these goals other means such as combinational or analogical processes are essential in addition to the basic knowledge to reach the creative results.

Creativity involves four components: the creative process, creative product, creative person, and creative situation (Eysenck 1994). Several variables interact to produce creativity. He divided these variables into cognitive, personality, and environmental ones. Cognitive variables like intelligence, knowledge, technical skills, and special talents. Environmental variables like politico-religious factors, cultural factors, socioeconomic factors, and educational factors. Personality variables like internal motivation, confidence, non-conformity, and creativity (trait).

Creative methods usually work by increasing the flow of ideas, removing mental blocks, and widening the search area for solutions (Cross 2000). These creative methods can be achieved by using special type of tools. For example to increase the flow of ideas brainstorming can be used to produce a large number of alternatives. Furthermore, the use of analogical thinking can eliminate mental blocks. On the other hand widening the search space can be achieved through transformation, random input, why questions, and counter planning. Moreover Cross (2000) addressed the creative process and divided it into five stages namely: recognition, preparation, incubation, illumination, and verification.

It is recognized from the literature discussed above that creativity is a multi-disciplinary field of study which can affect human thinking in various disciplines. It is affected by several issues concerning human cognition, environment, tools, and methodologies.

2.3.2. Creativity in Design

In the previous section about creativity, a general summary of the nature of creativity was discussed. In this section the focus is on creative design thinking presenting a summary of the creative design processes, models and tools, evaluation and computer support from the literature focusing on creative design.

2.3.2.1 *Creative Design Process*

Simon (1988) hypothesized that creativity is a special kind of problem solving behaviour which satisfies novelty and value of the product for the designer or his culture, unconventional thinking, high motivation and persistence, and ill defined problems to be formulated through the design process. His model was based on the personal view of creativity.

Alternatively, Csikszentmihalyi (1988, 1996) developed the social-cultural creativity model on where is creativity not on what is creativity. He proposed a dynamic framework composed of three major elements: the person, the field, and the domain. The occurrence of a creative idea, object, or action is determined by the jointly relation between those three elements. An idea is realized as creative if the person recognizes it and the society as well.

Liu (2000) combined Simon (1988) and Csikszentmihalyi (1988, 1996) creativity models to come up with the dual generate-and-test model. The dual model encapsulates two generate-and-test loops; one at the level of the individual, and the other at the level of society. Creativity can be found in the interaction between these elements. The individual searches

and generates a solution and tests his outcome in a generate-test loop. If the solution is recognized as creative to the individual it will be passed to the field (society) to be tested for creativity. The recognized creative ideas are then stored in the domain. Conversely the uncreative ones are sent back to the individual to start the (generate- test) loop again.

Based on concepts from creative cognition Tang and Gero (2002) proposed a cognitive method to measure creativity in design. They measured the cognitive behaviours of designers rather than the process itself. These cognitive events when accumulated resulted in the outcome of the process. They introduced a new level under the individual area in Csikszentmihalyi's system which is the design process. The concept of creativity is generated from the interaction between those four areas.

On the other hand Cross (1997) discussed the different descriptive models of creative design which are: combination, mutation, analogy, first principles, and emergence through an example of a 'creative leap' which occurred during a recorded design activity of a design team. He concluded that the perceptual act underlying creative insight in design is more similar to bridging than leaping the gap between problem and solution.

Sugiyama et al. (1997) discussed the emergent process or idea creation process which can be applied in problem solving and conceptual design. It included the following steps: (1) identifying the problem, (2) collecting relative information to the problem, (3) organizing the collected data into structured forms to be visualized, and (4) presenting these structured forms to the users. They developed the Emergent Media Environment (EME) system which applied the emergent process they discussed. Their EME system included three major steps which are: (1) the generation/collection step, (2) the organization step, and (3) the presentation step. Their developed EME was not evaluated on practical design problems although it provided useful concepts in design environment but still did not support complexity in design.

Candy (1997) described the creative process in terms of three stages. The first stage is about generation and invention; it involves creation of new ideas and new rules. The second stage is about exploration and evaluation; it involves shifting the balance between human and computer through examining data, evaluating, and refining rules. The third stage is about consideration of constraints; it involves receiving, clarifying, and revising the constraints. Furthermore, she clarified the various elements of creative cognition and she implied if these elements are combined together the result is creative. These elements include: problem formulation, ideas generation, strategies, methods, and expert knowledge.

Gero (2000) presented various creative design processes which were recognized for their efficiency in producing creative design solutions. The presented processes were described as promising because computational aids can be built using them to enhance the creative design thinking process. These described processes include: combination, transformation, analogy, emergence, and first principles. Gero presented a basic computational description of each process without too much detailing in the implementation schemes that need to be applied.

Dorst (2001) discussed the co-evolution of problem-solution in the creative design process. He added creative design is not fixing the problem and searching for solution, it is more into developing and refining both the problem formulation and the solution. This can be achieved by the continuous repetition of analysis, synthesis and evaluation processes between the problem space and the solution space. The problem and solution spaces co-evolve together with information exchange between both.

Hsiao and Chou (2004) proposed a creativity-based design process integrating some systematic design methodologies with the creativity method. The method contains four personal behaviours of human sensuousness and one extrinsic influence of the environment: looking, thinking, comparing, describing, and stimulation. The proposed design process included three essential stages: divergence, transformation, and convergence.

More design strategies or disciplines of innovation were described by Petre (2004). The study was based on observation of several companies that uncovered the deliberate practices of these companies to support innovation. It was recognized that innovation happens deliberately using such systematic practices. One of the major practices was systematic knowledge acquisition through search, technical literature reviews, analysis of legislation requirements and regulations, and review of competitions in the market. Several practices were described as well namely: collection of loose possibilities, record keeping, reflection on completed projects, systematic reuse of recent innovations, identification of barriers, attention to conflicts, brainstorming, gap finding or exploration of possibilities, scenario reasoning and consequences, stripping down to fundamentals, considering essences, systematic variation in constraints, and playing with toys (investigating other people's widgets and developing pet ideas). All these practices supported innovation in the studied companies. Such practices constitute the basis to build any design computational systems to support creativity and innovation since they proved their competency in real practices.

The limited Commitment Mode (LCM) strategy in the creative design process was considered by Kim et al. (2007) to study the difference between expert and novice designers. LCM strategy was based on the decomposition of the design problem into sub-modules. While working on any particular module the designer is not forced to finalize it before moving to another one. The designer is allowed to put any module on hold, try working on other sub-modules and then come back to the earlier one later. From Kim et al study it was recognized that there were some differences between expert and novice designers while solving the design problems. Experts were more active in using the LCM strategy than novices. Furthermore, experts take more time to decide design concepts (had later decisions) and the later the concept was decided the more creative the results were. Another difference was in the use of cognitive aspects where each group used different cognitive aspects in solving the design problems. This shows that experience plays an important role in the adopted design processes and the produced solutions.

Several researchers discussed the creative design process from different views including personal and social-cultural. General steps of the creative design process were proposed and presented. These steps were focused on the early design stages which are concerned with identifying the design problem and generating conceptual solutions for that problem. This indicates the importance of this early stage of the design process in producing creative solutions. Nevertheless the whole design process should be integrated within any creative design environment since creativity can occur at any stage of this process.

2.3.2.2 *Creative Design Models and Support Tools*

Several models to study and understand creative thinking in various disciplines were addressed in the literature. Some other models were proposed to produce creativity and not to understand creativity. Once the understanding of this phenomenal process is achieved; developing proper tools to enhance it is to take place.

Plsek (1996) discussed several models of creative thinking starting from the early twenties of the twentieth century. Older models involved subconscious processes outside the control of the individual for creative ideas generation, while modern models implied that the individual controls the purposeful generation of creative ideas. Furthermore it was indicated that the total creative process is a balance of imagination and analysis which requires action and implementation of generated ideas.

Furthermore, Plsek (1997) proposed a model (directed creativity) for the creative process in four phases: preparation, imagination, development, and action. Despite the different tools to support creativity, all tools are based on three simple principles namely: attention, escape, and movement. When developing techniques to enhance creative thinking, as long as they have elements that focus attention, provide escape from the problem's mental

patterns, and encourage flexible mental movements, it is assured that they will be successful.

Computational tools support interaction between the designer and the materials they provide to solve design problem situations. The interaction design of such tools should facilitate the generation and manipulation of design representations to enhance the designers' cognitive processes. Tools are meant to be designed based on the type of design representations they support. Yamamoto and Nakakoji (2005) argued that design-centred approach for tools' interaction is essential in developing computational tools that externalise knowledge for designers to interact with. They derived three interaction design principles for such tools:

1. To support design representations that are interpretation-rich to be perceived and recognized in various ways.
2. To support representations with constant groundings, to be easily mapped to a specific situation of the design problem.
3. To support design representations that can be generated and manipulated by the designers using interaction methods such as hand-drawing sketches.

Designers usually consider a large space of design solution possibilities in order to solve design problems. The changing nature of design problems requires general purpose tools to comply with these various situations. Some tools can support the design process by being specialised and customised for certain design types, while some other tools can be general in its purpose and designers can fit them to specific and various design problem situations. Current design interfaces do not support the non-linearity and the exploratory nature of design processes in their structure. Applications usually support viewing one design state at a time and eventually lock designers into a linear interaction mode. This linear interaction mode does not support simultaneous exploration of various design concepts which can hinder the creative design process. To help bridge the gap between design practices and computational tools, Terry and Mynatt (2005) presented the multi-state previewing tools which included: multiple previews, side views, design galleries, spreadsheet-like interfaces,

subjunctive interfaces, and suggestive interfaces. Furthermore, they introduced a framework for multi-state previewing tools which incorporated the following components:

- Command selection
- Argument selection
- Iterative function application
- Output filter
- Presentation mechanism
- Refinement
- Selection

This framework provided a guide to building such tools by dividing them into segments which can be solely studied and enhanced and offered a structure to facilitate viewing, comparison and evaluation. Therefore the individual and the tools adopted play an important role in modern creative thinking models for they strongly affect the generation of ideas.

Akin and Akin (1996) aimed to understand the creative thinking among designers by proposing a model to observe the mental insight in design and discovery. Their model encompassed four modules namely: alternative solution module (AM), problem formulation module (PM), interpreter module (IM), and generator module (GM). The AM module is the major medium of design representations. It was linked with an intelligent CAD system to facilitate visualization. A large search space and navigation tools are also incorporated. The PM module keeps records of current and past problem formulations. It contained aspects, goals and methods which can be associated variably to formulate new problems. The IM and GM are the procedural modules in the model. The IM is concerned with detecting the useful patterns in the design representations and the potential creative ones, while the GM module is involved in the constructing and modifying of those representations. In this model it is possible to study the induction of creative flashes, and the relation between these flashes and rules or constraints. Furthermore, the relation between the declarative and procedural knowledge can be appointed and their effect on the

induction of creative flashes can be recognized. The role of visualization can be explored as well.

Kokotovich (2000) examined creative design issues; mental synthesis, and drawing between 3D designers, 2D designers, and non-designers. He concluded that designers are more creative than non-designers when given creative mental synthesis tasks. Furthermore, how and when drawing is used is important. Hence drawing and design representation play an important role in the design thinking process.

Van Der Lugt (2000) investigated graphic tools for creative problem solving in design teams. He applied different types of brainstorming tools namely: visual and classic brainstorming. The linkography method was also investigated to define direct and indirect connections between ideas. He concluded that including visual expression into creative design meetings can change the characteristics of the solving process.

Sketching in creative problem solving is an iterative process that comprises evolvement of rapid various constraints (Sedivy and Johnson 2000). A multimodal sketching tool was developed based on the requirements established from their theoretical and empirical studies. The developed tool supported rapid production of design ideas through encompassing several features. It allowed a quick access to functionality, supported the use of layers like tracing paper for sketch modifications, provided various pencil thicknesses and colour intensities, allowed manipulations on drawings, supported the expected aesthetics like the sketchy look, and provided the maximum screen space for drawing with minimal palettes and widgets. The tool was developed for sketching characters in animation and illustration. It is purely drawing with no extra use of knowledge or other requirements, all these aspects need to be stored in the users mind. Nevertheless, one of the major advantages of the tool is that it provided speech input beside the use of menus. It was stated by the users that the speech input would increase productivity because it is faster and allows continuity of thoughts without distractions.

Concept mapping is a way of externalizing the learnt knowledge. These structured knowledge representations can be accessed and refined or expanded through different design processes. Representation of the knowledge domain in a form that can be comprehended and used successfully is very essential in the conceptual understanding of that knowledge domain. Anderson and Abdalla (2002) and Anderson (2002) developed a concept mapping tool and incorporated it within their proposed collaborative system for distributed information sharing. This concept map was derived from the brainstorming diagrams used in the design team meetings.

Oxman (2004) developed the Issue-Concept-Form (ICF) model which is based on decomposition of a previous knowledge into chunks. A typical chunk links issues of the design problem with a particular concept solution and a related form of the design description. Based on the ICF model, Oxman (2004) developed Web-Pad tool for concept mapping which is constituted of several modules integrated within the tool architecture. Web-Pad tool provides an interface for case representation forms; it has the facility for construction and extension of the concept base, indexing method for storing and retrieval of design concepts, and encompasses different search mechanisms for retrieving similar relevant design cases using conceptual links and semantic relationships.

Cognitive maps are not considered graphical representation of what is said or thought. They represent a way of interpretation of reflective thinking and problem solving. Maps are mainly structured using nodes and links between nodes with the properties of hierarchy and linkage (Eden 2004). He presented a range of possible analyses of cognitive maps. These analyses provide indications of features of the map and enable emerging features to be detected. He presented seven types of analysis which should be achieved with the help of computation. The analyses are: islands of themes (clusters - without accounting for hierarchy), networks of problems (clusters - accounting for hierarchy), finding potent options, virtuous and vicious circles, central concepts as the “nub of the issue”, simplifying the issue through emergent properties, and shape.

Usually a concept map includes nodes, linking lines, and linking phrases. Nodes represent terms or concepts, linking lines usually have unidirectional arrows from one concept to another, and the linking phrases describe the relationship between nodes or concepts. The arrangement of the concepts and the orientation of the linking lines determine the map structure (Yin et al. 2005). Five key concept map structures were described: the linear, the circular, the hub/spokes, the tree, and the network/net structure. The network/net structure is considered the most complex one. Two techniques for constructing concept maps were discussed and tested. The (C) technique; constructs a map with created linking phrases, and the (S) technique; constructs a map with selected linking phrases. It was concluded that the two techniques are not equivalent. The C technique was better in capturing partial knowledge while the S technique was more efficient.

Non-hierarchical concept maps present a holistic approach by making the structure of the problem more readable. They also act as memory aids to review the design problem at any stage of the design process (Kokotovich 2007). It was found that the use of non-hierarchical maps in the early design processes is linked to the development of creative design solutions. It was also recognized that the greater the number of issues raised at these early stages the greater the possibility of producing creative results. Furthermore, it was noticed that this type of concept maps can guide novice designers in adopting expert designers' processes which leads to more creative results.

Analogical reasoning is a commonly used technique in problem solving. It is the transfer of knowledge between various domains based on similarities between the target and the source space (Gero and Kazakov 1999; Gero 2000). Analogical reasoning processes include: transformational analogies, and derivational analogies. Transformational analogies adapt structures of past solution to new design problems, while derivational analogies usually apply a successful well known process to the process of producing a new design concept. Analogical reasoning involves three major phases: (1) identifying the source candidates for analogy (matching and retrieval) where the design alternative with the highest degree of similarity between the source and the target design spaces is retrieved, (2)

mapping the source candidate with the target by adding some design variables from the source design space to the target design space, and (3) transferring knowledge between the source and the target. The analogy affects the structure of the design concepts by introducing new variables into the original structure.

Gero and Kulinski (2000) developed a system for situated analogy in designing. They took into consideration the notions of unexpected discoveries, s-inventions, and modifiable design goals through the interaction of four agents namely: the prototype chooser agent, the representation agent, the perceptual agent, and the analogy maker agent.

Two main strategies for matching and retrieval in analogical reasoning were introduced namely: semantic-based retrieval, and structure-based retrieval (Gomes et al. 2006). They used analogical reasoning in REBUILDER which is a system for software design developed by them. Selection of the appropriate candidate was based on retrieval and ranking of the retrieved results according to a set of metrics. Three different metrics were used: the first combined the semantic and structure evaluation, the second used an independence measure, while the third used structural properties. The mapping process was either relation mapping or object mapping. For each mapping a new diagram was created which was a copy of the target solution, and then the algorithm transfers the knowledge from the candidate to the new created diagram. This transfer is either external or internal object transfer. Furthermore, they explored the relation between the analogy strategy used and the novelty of the results. It was recognized that semantic retrieval generated more useful results but less novel. Using of both the semantic and structure strategies indicated, it was a better retrieval option.

The literature review revealed that few creative design models and tools were developed. These models focused on specific tool in applications without taking into consideration other factors that can have great impact on the creative design environment. Some of the creative tools such as brainstorming, concept mapping, analogical reasoning, and sketching

were discussed. This discussion provided a wide scope of some of the creative tools which can be useful in developing creative design environment.

2.3.2.3 *Creative Design Evaluation*

One of the most important issues in developing creative design environments is the evaluation of the generated design concepts in order to select the most creative ones for further development. Various approaches have been discussed in the literature to evaluate design alternatives. Some of these relevant approaches are summarized in this section.

Pugh (1991) developed concept selection charts which proved to be very effective in the early stages of design where the concepts are still very abstract and minimal detailing is available. They can also be effective at later stages when the knowledge detailing increases and the scales of selection are refined. The design alternatives and the evaluation criteria are displayed jointly on Pugh charts. The design concepts constitute the top row of the chart, and the evaluation criteria constitute the first column of the same chart. The evaluation scale Pugh uses for preliminary concepts was based on minimal scale of only {-, s, +}. His evaluation scale starts by selecting one alternative that will be ranked as {s} which he called the *datum*. All other concepts will be compared to this datum and will be given a rank of {s} if the same as datum, or {-} if worse, and {+} if better. The evaluation scale can be changed to numerical ranking at later stages where more design knowledge is available.

Debate of creativity evaluation interested many researchers. Boden (1994) discussed that creative ideas cannot be assessed by a scalar metric; instead the appropriate method of assessment would have to take into account the fact that conceptual spaces are multi-dimensional structures, where some features are deeper and more influential, than others.

Otto and Wood (2001) described the selection process of design alternatives and divided it into five steps plus iterations as required. These steps are: (1) establishing the evaluation criteria, (2) establishing the design alternatives to be evaluated, (3) ranking the alternatives, (4) evaluating the alternatives, and (5) attacking the negatives. They claimed that the design team should consider one criterion at a time and rank all the concepts on each criterion before moving to the next one. Furthermore, the ranking of concepts need to be aggregated into one or more ranks to simplify the ordering of concepts in a best-to-worst ranking and to assist designers in processing these ranks.

Chuang et al. (2001) examined the relationship between user preference perception of mobile phones and their form design elements. It was recognized that users prefer mobile phone designs with soft and compact images. Therefore, they proposed design preference models which are composed of relative weights of design elements that reflect specific design trends. Finally, a computational approach to search for the optimal solutions for preference as well as for the design trends of soft and compact was proposed.

McDonagh et al. (2002) discussed a user-centred approach in design evaluation of products. They focused on emotional responses from users and how to support users in communicating these emotions and attitudes to designers. Various qualitative techniques were developed and presented namely: product personality profiling, mood boards, and visual product evaluation. Product personality profiling involves imagining a product as a person with personality; the user needs to provide information about this product's character and life style. The interpretation of results in this technique can be complex and not easy to handle. Mood boards can be used by designers and users, its theme involves creating boards using images which express the creator emotions such as happiness, sadness, and calmness. They enable communication which is beyond linguistic restrictions and visual stimuli for designers and users simultaneously but it requires availability of suitable images and requires skills in interpretation. Visual Product Evaluation was based on the use of rating scales and short comments through forms and questionnaires. This

technique can be time consuming to prepare in advance and forms can restrict user responses.

Furthermore, Rashid et al. (2004) presented evaluation criteria for the aesthetics of products. They surveyed several aesthetic attributes namely: shape, size, colour, weight, transparency, cap, and materials. These attributes were used to evaluate soft drink and mineral water bottles. They used questionnaires to collect people's viewpoint. The concluded findings provided the basis for a knowledge-based design system. These findings include: circular genre shape is preferred, surface shape should be curved smoothly finished, or gradually changed over, clear or blue colours are preferred for water bottles but other colours can be used for other types of drink bottles, one single colour is dominant, medium size for principal range while small and large sizes can be taken for secondary considerations, a light, low cost, and environmentally friendly material is preferred, and finally sports cap or conventional caps can be chosen depending on the age of the target customers.

Hsiao and Chen (2006) investigated the structure of the relationship between product shapes and affective responses. They conducted three parallel studies to uncover fundamental dimensions of affective responses to product shapes using three different product categories representing large, medium, and small products. As a result of these studies, they proposed four fundamental dimensions: the trend factor (T), the emotion factor (E), the complexity factor (C), and the potency factor (P). These dimensions provided a common framework for studies on affective responses to product shapes.

On the other hand, Lee et al. (2006) presented a systematic methodology, named systematic evaluation methodology for cell phone user interfaces (SEM-CPU), to evaluate user interfaces of cell phones. It was based on integrating five empirical methods namely: scenario-based task performance, questionnaires, retrospective think aloud, post-task interviews, and user observation in laboratory settings. The study aims were to discover valid usability problems and to generate suitable design specifications through three stages:

data collection, analysis, and integration. In the first stage different types of data are collected using the five empirical methods described earlier. The second stage analyses the collected data using two analysis types: quantitative and qualitative. In the third stage the designer identifies specifications and guidelines by integrating all data collected.

Tsai et al. (2006) developed two evaluation models and applied these models in a case study of an electronic door lock design. The first model used fuzzy neural network to predict the overall image, while the second model uses gray (where information is partially unknown) clustering operation for the colour image evaluation and two fuzzy neural networks for the form image evaluation. Their results showed that the image prediction capability of model II is superior to that of model I. they used the superior model to develop a cumulative design interface integrated with a professional CAD system in order to demonstrate the effectiveness of the image evaluation approach.

Human Computer Interaction (HCI) of various CAD systems was evaluated by Sener and Wormald (2008). In their research study several HCI concepts for CAD tools were generated and evaluated according to specific criteria. Their evaluation aims were to identify the most favoured and least favoured alternatives in addition to the features and characters of each concept that led to each specific evaluation. Each generated concept was evaluated individually against three evaluation criteria which included: enjoyment, inspiration, and assistance. These criteria evaluation when combined can give a good assessment of the desirability of the concepts.

The research studies presented in the literature review provided a good base to start from in developing the evaluation stage in the creative design process. Although each design problem has its own boundaries and objectives, a generic approach can be reached in choosing the evaluation criteria in such various situations. These presented concepts in evaluation can be developed and enhanced to fit the scope of this research.

2.4 Design Computation

Several researchers tackled the area of computation in design and how it can be utilised to enhance the creative design thinking. Some of the studies argued whether computation can enhance creative design thinking, others suggested guidelines and characteristics of such systems and tried to apply some of them, while some others discussed the application of different computational tools to increase the creative production of individuals.

Computational modelling is a computer program for which certain special and often complex claims are made (Partridge and Rowe 1994). They declared that a computational model may be a mechanistic model or/and an input/output (functional) model. Furthermore, Liu et al. (2004) indicated that creativity is not easily converted into a computational tool for it is a human feature and that computational tools do not stimulate creativity but do stimulate the designer to catch sudden inspiration by exploring innovative designs more easily.

Gero (1990) described a knowledge representation schema for design called design prototypes. Design prototypes were shown to provide suitable framework to distinguish routine, innovative and creative design. The described design representation was divided into several parts namely: function, behaviour (actual and expected), structure, design description, context, and knowledge (relational qualitative, computational, context, and design prototype knowledge). Using such knowledge representations in design computation separates the knowledge from the computational processes; it also provides a translator between structure and function.

Hori (1997) discussed creativity in design and if it can be triggered by computer systems. He argued if the systems can force the designers to get out of the routine design space and start thinking of new design strategies to change the concept space. His proposed system tested two types of design strategies: abandonment strategy and new knowledge strategy. Usually designers stick to the strategies that will solve the problems and achieve all the

requirements. If the designer abandons some of these requirements a new concept space can emerge. Therefore new more solutions can be situated. Furthermore, introducing new knowledge can change the design space with more creative solutions to be located. The system did not force the designer to choose a specific strategy. The visualisation and exploration of the concept space made the designer perceive the strategies he/she can use.

Candy and Edmonds (1996) categorized the elements of creative design into problem formulation, ideas generation, strategies, methods, and expertise. They argued that computer-based design must provide flexible and usable support which complements the designer thinking processes. Various directions for future design support systems were proposed in respect of the key issues concerning interaction with design knowledge. Interactive knowledge support systems should address the exploratory processes of design by providing fluent interaction between designers and knowledge. This can be achieved through multiple and parallel viewing of information and a flexible interactive dialogue for handling the information. Methods are required to let the designer modify and create new knowledge during the design development with the ability to switch between tasks in order to interact with parallel design knowledge to be used whenever required. Furthermore, mechanisms for the communication of design knowledge should be addressed. Uncertainty should also be supported. Methods for the identification and formulation of the design problem should be provided with the ability to maintain the strategic knowledge that designers use during the design process.

In another study Candy and Edmonds (1997) discussed the role of criteria in design and proposed a criteria-based modelling approach to interactive system design. Several criteria types were listed namely: behavioural, compositional, symbolic, preferential, pragmatic, performance, and contextual.

Domain-Oriented Design Environments (DODEs) to support design creativity have been developed and presented by Fischer and Nakakoji (1997). DODEs are computational media that provide users with environments that allow them to be engaged in more design tasks by

supporting human problem-domain interaction. They support design processes by identifying shared design representations that allow task-based indexing of cases and design rationale. Task-relevant knowledge is delivered to users and back-talk of the artefacts is increased to support designers. Usually new representations are needed to solve the task at hand and mechanisms are needed to increase the artefacts back-talk. Three different types of support systems were implemented in various domains focusing on critiquing mechanisms to support reflection-in-action through the design process: Knowing-In-Design (KID) for kitchen plan design, Interactive Abductive Mechanism on an Environment for MultiMedia Design (IAM-EMMA) uses abduction mechanism to support designers in selecting pictures for a certain design task from image library, and Amplifying Representational Talkback (ART) for supporting writers in the early stages of creating documents (Nakakoji et al. 1998). All three systems support designers in recognizing implicit features in design situations, although each one of them uses a different mechanism. KID uses (active) critiquing mechanism to identify problem and retrieve relevant information. IAM-EMMA uses abduction to understand requirements and to suggest modifications (passive critiquing mechanism). ART uses representational talkback to allow designers to use external representations to uncover implicit features (implicit critiquing mechanism). Based on their assessments of the three systems they proposed four requirements for such systems to support uncovering hidden features in design: provide tools to explicitly represent problem's requirements and solutions, allow designers to modify feedbacks and argue against feedbacks, provide explanations, and utilise the external representation as feedback.

Understanding the creative processes can be the basis to construct information technologies with effective tools that might assist designers in their creative design tasks. Therefore, Shneiderman (2000) proposed a four-phase framework for creativity which might help in providing effective tools for designers in such information technology systems. The first phase is *collect* where the designers learn from previous works stored in the digital libraries, the web, databases, etc. the second phase is *relate* where designers consult colleagues, clients, managers through all design stages (collaboration). The third phase is

the *create* phase where designers explore, compose, and evaluate design alternatives. The fourth and final phase is the *donate* phase where designers disseminate the solutions and contribute to the digital libraries or databases. Within this described framework Shneiderman (2000, p.19) proposed eight activities that should be offered by any integrated creativity support tools. “(1) *Searching and browsing digital libraries* (2) *Consulting with peers and members* (3) *Visualising data and processes* (4) *Thinking by free associations* (5) *Exploring solution-What if tools* (6) *Composing artefacts and performances* (7) *Reviewing and replaying session histories* (8) *Disseminating results.*” The integration of all these activities in one system could produce a support tool that enhances creativity.

Hewett (2005) discussed the importance and the nature of insight by defining the conditions required to foster it and showing the importance of external representation to facilitate the occurrence of that insight. The working environment can inhibit creativity or it can support the occurrence of insight by minimizing the known factors that work against its development or occurrence. For example creativity is not likely to occur without motivation, without consulting with others to build a solid grounding in ones domain. The creation of external representations can be useful to the thinking about the problem in hand. External representations can have various forms such as drawing, making models, diagrams, and printing intermediate results. Hewett (2005, pp. 396-397) proposed several factors which facilitate the possibility of insight in Problem Solving Environments (PSEs) namely: “(1) *Provide a library of macros and analogs* (2) *Make possible multiple alternative representations of domain-based problems* (3) *Allow those multiple problem representations to be simultaneous so that they can be compared and tested and evaluated* (4) *Allow for flexible and tailorable usage of the working environment* (5) *Allow multiple configurations of the working environment and its tools that can be saved and restarted so that having to work on multiple projects does not require a shut down and re-assembly every time the problem solver switches their attention from one problem to another* (6) *Support a variety of multiple store and find operations* (7) *Provide multiple access routes into archives and repositories or relevant data or other information* (8) *Log processes and*

intermediate results to enable the user to easily recapture these results (9) Make it possible for the user to re-configure or re-define the problem domain.”

Requirements for tools to support two specific tasks which are considered creative are presented by Johnson and Carruthers (2006). These two tasks are poem writing and poster designing. Since our interest is in design we will mention the requirements of the poster tool only which can be summarized as follows: *“(1) Provide a theme giver (2)Support for planning/sketching of ideas (3) the ability to add/create objects (4) the ability to explore different layouts (5) the ability to manipulate objects in an arbitrary manner, including editing and formatting (6) provide browse-able/searchable poster specific image libraries (7) the ability to arrange workspace (8) provide examples of styles, layouts, fonts and colours that are effective (9) the ability to position objects in an arbitrary manner, including overlapping and layering (10) provide a selection of predetermined poster shapes as opposed to specific dimensions (11) support automatic scaling of the poster to fit arbitrary sized media without degradation in resultant image quality (12) the ability to view rough plan at same time as actual poster (13) support the use of layers e.g. for tracing (14) support import to and export from other applications, including the internet.”* These requirements are obviously proposed for poster design specifically, but it is possible to make use of such requirements in other design domains as needed. It is recognizable that these requirements focus on flexibility and exploration which are vital ingredients for support tools in design.

Alternatively, Soufi and Edmonds (1996) explored emergence in design computation in more detail. They developed a framework considering the cognitive processes that give rise to emergence in addition to its representation. Requirements for a computational model that represents different types of emergence and supports the user’s interaction were identified.

Design computation can trigger creativity in design through several issues such as introducing new knowledge, visualisation, and interaction to complement the designers’ thinking processes. Guidelines for future design systems were proposed which can be very

useful to be considered in developing such systems. Some of the presented systems discussed and implemented some design computational concepts, but they lacked the holistic approach of creative design computational environments.

2.4.1 Situated Creativity and Design Computation

Situatedness is a well known terminology in creative design research which identifies the fact that designers work within an environment which affects their design activities. Each design problem has its own situation which can produce different boundaries and requirements each time a designer explores the design environment for solutions.

Gero and Fujii (2000) proposed a framework for concept formation in designing that has the potential to deal with the aspects of situatedness and emergence. The structure of each design agent includes sensors, preceptors and conceptors that interact with each other and with the external and internal environment of the agent to produce the situation that is a contingent basis for concept formation.

Furthermore, Gero and Saunders (2000) discussed the constructive presentations produced by situated computational processes and their functions in computational models of designing. They also discussed the importance of design emergence that can expand a design space and facilitate creative designing.

Conversely, Gero (1999, 2000, 2003) and Gero and Kannengiesser (2004) developed the Function Behaviour Structure (FBS) framework which involves several creative design processes: *formulation, synthesis, analysis, evaluation, reformulation*, and finally *production of design description*. They described the situatedness concept as a recursive inter-relationship between different environments, the external, internal and interpreted worlds. They concluded that with situated computing it is possible to produce tools that learn from their experiences and apply what was learnt within both like and new situations. Gero (2000) described a framework for a computational process based on five creative

models: combination, mutation, analogy, emergence, and first principles. Each model of them was investigated and a computation representation was developed considering main concepts behind each single model.

Gero and Sosa (2002) and Sosa and Gero (2003, 2004) presented the Creative Design Situations (CDS) model which studied social creativity through the computational implementation of a community of creative design agents. They studied the interaction between designers and social groups and the change phenomena in design.

Some research studies discussed visualisation in design computation from various perspectives. Nakakoji et al. (2000) discussed two computer systems to support designers' creativity through the use of representations created by others in the community. They concluded that using rationale visual images in computer systems can help designers in their creative design. Whereas Lewis (2000) added that high-end Computer Graphics (CG) software packages have in recent years become sufficiently robust to allow for flexible specification and construction of high-level procedural models in addition to extensibility allowing for the creation of new software tools. One component of these systems is the visual data flow network. One of the CG packages to employ this paradigm was Houdini. On the other hand, a research study by Cha and Gero (2005) discussed the visual side of design computation. They investigated properties of shape pattern schemas to represent shape patterns as formative ideas for supporting design computation. They identified shape pattern knowledge from physical shape primitives and spatial relationships to support innovative and creative design.

Moreover, artificial creativity promotes the study of the creative behaviour of individuals and societies in artificial societies of agents. It provides an opportunity to study the emergence of creative behaviour in controllable environments and develops better understanding of the situatedness of creative processes within socio-cultural situations. Saunders and Gero (2001a, 2001b) presented a computational model of creativity that attempts to capture within a social context an important aspect of the design process: the

search for novelty. The system consisted of multiple artificial design agents equipped with an evolutionary art system to generate genetic artworks, a neural network, and was capable of learning as it explores the space of possible genetic artworks.

Gero and Kannengiesser (2003) presented an approach to product modelling through using situated computational agents. These agents produce data representations based on the specific requirement of the current situation. Their research laid the foundation of a different type of tools that are more intelligent in their ability to learn by being used. Furthermore, Smith and Gero (2005) investigated the meaning of situated artificial design agents in different fields. By applying the notions of agent-ness, rationality, and indexicality it was possible to say what a situation and what situatedness are. Furthermore, applying the same notions to embodied action and constructive memory allowed the consideration of how such representations might be acquired and constructed. The definition of artificial creative work is thus a social construct of more than one agent and creativity is an honorary term given to agents that consistently produced artworks appreciated by other agents.

Situatedness in design was discussed in the literature by several researchers. The majority of them concentrated on developing systems which deal with artificial agents to model situatedness in design. In their research work they cancelled the important role that human designers play in any creative design environment through focusing on the development of artificial intelligence applications which can be useful in studying the effect of such concepts but not for real life problem solutions.

2.4.2 Evolutionary Creativity Computation

The development of evolutionary design tools is still at its early stage. The research and development of creative support tools using evolutionary design computing are still in process and have huge potential for the development of new creative design technology.

Bentley (1997) and Bentley and Corne (2002) discussed that evolutionary computation is all about search. Evolutionary search algorithms look at a population of slightly different solutions at once, and then through mutation and reproduction, new generations are created and evaluated until objectives are met. Four new 'overlapping' types of Evolutionary Design were suggested and different common problems of such systems were discussed such as interdependent elements in designs, and constraint handling.

Bentley and Wakefield (1996) developed a prototype design system which uses a genetic algorithm to evolve new conceptual designs from scratch without the input of preliminary designs. It demonstrated that evolutionary search is capable of optimising designs and creating new conceptual ones. For more complex design tasks, the system created new designs from previously created components.

Gero and Kazakov (1999) introduced a modification to genetic algorithms which provides computational support to creative designing by adaptively exploring design structure spaces. This process is more general for it is cross-object and not cross-image interpolation. Two classes of applicable expansion or modification operators were discussed; first, operators which rely largely on external knowledge, second, operators which make use of emergent features in design.

Furthermore, Liu et al. (2004) presented a visual evolutionary computing environment to support creative design. The 2D sketches and 3D images can be generated by combination of evolutionary computing and visualization technology in that environment. This environment was used to stimulate the imagination of designers, activate their "eye in mind", and extend their design spaces.

In the presented literature it was recognized that evolutionary search can optimise designs and create new concepts based on visualisation technology and images. The presented

approach focused on the visual side ignoring any design knowledge necessary to create real creative design problem solutions.

2.5 Collaborative Product Design and Development

A definition of product design was given by Goel and Singh (2001) considering it a goal-oriented problem-solving activity that relies on human experience, creative thinking, and related knowledge; it should be practiced by integrating creativity tools with design methodology for durable and successful product development.

Collaboration is considered recently one of the important issues. Several researchers tackled this area of research from different point of views. Tseng and Abdalla (2004) and Tseng (2005) mentioned that effective collaborative design requires sharing information and resources between individuals and organisations. Therefore it requires a highly interactive integrated human-computer interface besides the groupware.

In another research Li et al. (2004) developed a system based on two collaboration manners which are a horizontal and a hierarchical manner. These collaboration manners are complementary in functions. They established a vertically linkage between the design and the manufacturing processes and a horizontally linkage of team work in the design phases. New feature-based formats and enhanced streaming technology for web applications were applied.

Girard and Robin (2006) introduced different types of collaboration which could be introduced in the design process to facilitate designers' tasks through setting the appropriate design environment. They proposed three main standpoints to develop collaboration and to manage collaborative design activities: definition of process, freedom of collaboration, and collaborative experience. The definition of process involves predetermined and unexpected collaboration. Freedom of collaboration involves three types: free, encouraged, and forced

collaboration. Collaborative experience involves established and non-established collaboration. Different types of collaboration can be obtained by combining all the different types with the three standpoints mentioned above to form twelve types.

Briggs (2006) discussed the use of theoretical models of cause-and-effect to develop on the technology-supported-collaboration-processes. He claimed that good theory can achieve unexpected design choices that can yield better outcomes for teams. It can be understood why other choices do not work as expected. In summary the key value of such an approach arises from the way it disciplines thinking. It provides clear articulation of the assumptions and logic which gives rise to the available technology choices to see more clearly and to discover new possibilities.

Carroll et al. (2006) suggested that people usually share activities not concepts in realistically complex circumstances. They described a framework for understanding collaboration in terms of four facets of activity awareness: common ground, communities of practice, social capital, and human development. They claimed that collaborators need to become and remain aware of one another in all four facets to work and learn together effectively. Furthermore, they derived four design requirements each associated with one of the described facets: public display of shared information, integration of data into community metaphors, aggregation of individual contributions into collective overviews, and contrast of individual capabilities and roles to invite collaborators to perform effectively.

On the other hand, Zha and Du (2006a, 2006b) developed and implemented a web-based knowledge-intensive framework for collaborative design modelling and support. The developed framework provided designers with an intelligent tool to collaboratively build integrated system models. The implemented system based on the preliminary application they conducted indicated some advantages to increase the efficiency of the design coordination and decision-making in the design process.

Tann and Shaw (2007) developed a knowledge-base collaboration modelling framework to support design using web-based data-sharing environment. It facilitated some applications through constructing 3D lines rapidly, translating the product data, and providing model configurations for XML type. It allowed sharing the web services from the internet to comply with specific strategies for each design case. Their framework proved that internet-based technology with information integration and coordination facilitates the development potential to collaborative design. Repetitive and tedious input and data inconsistency can be reduced by data exchange in such collaborative data-centric frameworks.

Kim and Maher (2008) studied the impact of Tangible User Interfaces (TUIs) on collaborative design. They revealed that the physical interaction with objects in the TUIs produced exploratory actions which changed designers' spatial cognition. Designers' perception of visuo-spatial information has been improved. They noticed a parallel increase in problem finding behaviours with the change in designers' spatial cognition. This in turn can lead to creative design.

The importance of inter-operability of product information among collaborative design enterprises has been discussed by Lee et al. (2008). To achieve inter-operability, they proposed product ontology architecture which consists of four axes: syntactic axis, theoretic axis, domain axis, and constructs axis. They introduced an extra new axis: evolving axis which reflects the evolving feature of product ontology. They concluded that collaboration through semantic synchronization can be supported by using product ontology architecture.

Chen et al. (2008) presented a distributed engineering knowledge management approach for the practice of Collaborative Product Design (CPD). They proposed a CPD-based engineering knowledge management methodology under the concepts of knowledge management and collaboration. Their methodology included a knowledge management-oriented engineering management work model, a distributed engineering knowledge management framework, and rules and methods for managing engineering knowledge. Their developed system provided a method for recording both explicit and tacit engineering

knowledge, and the reuse of engineering knowledge. They claimed that their developed model can be applied for other knowledge-intensive works such as software system development.

Several research studies in the literature discussed collaboration in product design and development. Different types of collaboration were recognized and few standpoints were developed to manage such collaborative activities. These types and standpoints can be useful in developing such creative design environments.

2.6 Summary

To summarise, the work reviewed that some creative design models were developed. Some of the developed models focused on creative processes, some focused on tools, and some other focused on knowledge. Furthermore, some models included few of the creative design factors necessary to creative design environments; none of them tackled the issue of creative design thinking from a holistic approach to include all the necessary factors for creative design systems. The key limitations of the reviewed work were that:

- Design models need more tools and techniques to enhance the design process.
- To support the design task more structured design knowledge is required.
- To minimise design fixation, inter-relation between various design domains is required.
- Lack of awareness of the problem identification and clarifying objectives in the creative design process.
- Few studies focused on the conceptual design procedures; there is a need to conduct more research in that area.
- There is a need to provide designers with sophisticated tools to support their ideas and facilitate visualisation of their concepts.

- A generic approach to evaluate creative design solutions which can be adapted to various design problem situations is recommended.
- Lack of holistic approach of creative design computational environments in the developed systems.
- The role of human designers in any computational creative design environment need to be addressed.
- Evolutionary computation need to consider design knowledge in addition to visualization technology.
- More research is needed to address collaborative activities in creative design environments.

It has been recognized through the literature survey that design is a learnt skill which can be enhanced by using proper concepts, methods, and tools to explore more creative ideas in the design space. Furthermore design computation has a great potential in developing future creative design systems to support design teams to minimize the product lead time from the early phases of design till the production processes. Since design is a nonlinear process a concurrent design platform will be useful in such systems. Several frameworks for creative design were discussed tackling particular areas in specific.

To overcome the shortcomings of the previous models described in the literature, a comprehensive Creative Design Tools (CDT) system is proposed. This system will provide the design team with the required knowledge databases, creative design tools, design processes, individual and team design environments within a concurrent design platform. The design team is the main core of the system which is meant to support the team instead of automating the design process. To achieve the aims and objectives of the research, the following stages are proposed:

- Formulate research and establish a suitable conceptual model for the analysis, design and evaluation of the proposed design system.
- Construct architecture for the visual computational model to increase creativity in design teams.

- Investigate the development of a computational model for creative design thinking
- Develop an integrated working prototype that stimulates creative design thinking
- Evaluate the above methods and tools through a case study.

CHAPTER THREE

CREATIVE DESIGN TOOLS AND PROCESSES

3.1 *Overview*

The use of creative design thinking tools, techniques, and processes has proven to be useful in enhancing designer's thinking through the various design phases. Designers tend to use some of these tools and process either deliberately or unconsciously. Creative design thinking has been discussed in the last century by many researchers from various aspects. The development of new technological advancements and global markets require more attention to that creativity issue in general and among designers in specific. Subsequent to a broad literature survey in the area of interest several creative design thinking tools, processes, and computation models were recognized.

To establish whether these tools, processes and computation models are in use among designers, a survey has been conducted by the researcher through interviewing designers in various design disciplines. Several issues have been discussed in the interviews which gave the author a comprehensive perception of how designers work and what they prefer. This chapter describes the research methodology adopted to carry out the interviews. The interviews results are discussed and their relevance to the proposed framework is outlined.

3.2 *Creative Design Tools and Processes*

A review of the related literature has been conducted ahead of interviewing the designers to investigate creative design tools and processes (i.e. tools used from conceptual design till the final detailed design ranging from brainstorming to evolution, systematic and creative design processes).

The creative tools established in the literature were mainly applied at the conceptual stage of the design process to enhance designers create more alternative options. It has been approved that they produce more creative outputs than the other conventional tools. Some of those tools are summarized in table 3.1.

Creative Design Tools	
1	Search and Widening Knowledge
2	Brainstorming
3	Concept Mapping
4	Analogy
5	Combination
6	Evolution
7	Emergence
8	Collaboration
9	Six Hats

Table 3.1 Creative design tools from the literature

The design process discussed in the majority of the literature was addressed as a nonlinear process. Although it has been referred to the design process as a linear one for ease of discussion; it is meant to be nonlinear and each designer approach the design problem from a different point at that design process. It has been recognized that one of the most important stages in enhancing creativity is the preparation stage. Preparation widens the designer’s knowledge and enriches it before incubation. Incubation involves digesting of that knowledge and sorting it in one’s mind (Shneiderman 2000; Cross 2000). Subsequently, various thinking methods and creative tools can be used to enforce the generation of creative and new concepts (Hsiao and Chou 2004; Petre 2004).

Concept generation is the main focal point of creative thinking. Various tools can be used to enhance the designer in his/her generation of ideas. In order to be creative, one’s mind needs to escape from the rational association of ideas and find new ways. The creative tools can help the designer to achieve this and form new associations and analogies.

Idea selection is another process which involves lots of creative thinking. Designers need to evaluate the created ideas with open mind on new potentials and capabilities of the proposed ideas. They should be capable of mixing and matching the elements of different ideas to produce a creative solution to the problem. A summary of the proposed design processes are summarized in table 3.2.

Design Stages	Stage Processes
Preparation	Client Meeting Problem formulation Research Data Analysis Data Synthesis Problem Reformulation
Idea Generation	Generating Concepts Organizing and Displaying Ideas Selecting
Evaluation	Individual Evaluation Team Evaluation Society Evaluation
Development	Selection Enhancement Documentation
Detailed Design	Specifications Working Drawings 3D Modeling

Table 3.2 Design processes

3.3 Empirical Survey

The next stage was to determine what creative tools are used by designers. The design process, evaluation criteria, design environment, computational tools have been also surveyed. The main objective of the survey was to reach a certain degree of understanding of how designers work, what do they use and need in their creative design process.

One-to-one interview scheme has been chosen to conduct the survey. It is a well known fact that interviews give a better response rate rather than any other type of survey like questionnaires. Furthermore, the potential of gathering relevant valuable information which can be useful for the research problem is more significant.

Therefore, a sample of 30 designers from various design disciplines has been chosen namely: spatial design, product design, graphic design and multimedia. The interview structure has been divided into 10 sections. The first section collected personal information about the designer age, gender, speciality, qualification and working experience. The second section was to enable designers explain their view of what creativity means to them. The third section managed to let the designers list the techniques they use to enhance their creative design thinking. The fourth section enabled designers to describe the methods they use for evaluation of creative design alternatives. The fifth section has been concerned with the design process that each designer follow to come up with creative results. The sixth and seventh sections enabled designers to mention the computer tools they use and if they think computers enhance or delay their work respectively. The eighth section managed to get the designers' opinion of design computation systems and if they find it helpful or not. The ninth section enabled designers to mention the working environment they believe could enhance their creative thinking. The last section enabled designers to add comments and any relevant suggestions regarding the area of interest.

By using this open ended structure of interview questions, the author managed to get more relevant creative design techniques, processes, evaluation criteria, and design environments

directly from the designers' practical views rather than affecting them by providing options to choose from. Although it is well known that such type of questions is much more difficult to analyse but it provides a more suitable results for this research problem.

3.4 Survey Results

The survey results have been based on 30 interviews conducted among designers. The SPSS application software has been used for the analysis of the data collected. The most common used descriptive statistics in this research study was the frequencies' tables and bar charts. The results are displayed in the following sections which represent the interview sections mentioned earlier.

3.4.1 Meaning of creativity

All designers have been asked about what creativity means to them. To analyse the data collected the author managed to categorize the commonly used catchphrases in the designers' definitions. The case summary of creativity catchphrases is displayed in table 3.3. The commonly catchphrases are listed in table 3.4 with frequency of occurrences and percentages of cases. The most commonly used catchphrase was new idea; it constituted 18% of the responses. The following catchphrase was new combinations or associations with a 9.8% of the responses. Interesting idea, different idea, inspiration, and talent each catchphrase of these constituted 4.9% of the responses. The other catchphrases constituted 3.3% or 1.6% of the responses.

The survey provided a various catchphrases regarding the meaning of creativity. It gave a general idea about the terminology used by designers regarding creativity. Although there has been no noticeable need for those catchphrases in the presented research, it has been

collected just to orient designers towards creative design thinking. It is akin to thinking out loud. These results have been presented here just for the sake of research reliability.

	Cases					
	Valid		Missing		Total	
	N	Percent %	N	Percent %	N	Percent %
Catchphrases (a)	29	96.7%	1	3.3%	30	100.0%

(a) Dichotomy group tabulated at value 1.

Table 3.3 Creativity catchphrases case summary

		Responses		Percent of Cases %
		N	Percent %	
Creativity Meaning Catchphrases (a)	New Idea	11	18.0%	37.9%
	New Solution Space	2	3.3%	6.9%
	New Ways of Thinking	1	1.6%	3.4%
	New Functionality	1	1.6%	3.4%
	Unique Idea	2	3.3%	6.9%
	Remarkable Idea	1	1.6%	3.4%
	Impressive Idea	1	1.6%	3.4%
	Interesting Idea	3	4.9%	10.3%
	Being Professional	1	1.6%	3.4%
	Different Idea	3	4.9%	10.3%
	Free Thinking	2	3.3%	6.9%
	No Constraints	1	1.6%	3.4%
	Needs Encouragement	2	3.3%	6.9%
	Problem Solving	1	1.6%	3.4%
	Sensitivity	1	1.6%	3.4%
	Useful Idea	2	3.3%	6.9%
	Change Surroundings	1	1.6%	3.4%
	Original Idea	2	3.3%	6.9%
	Exciting Idea	2	3.3%	6.9%
	Stimulating to Others	1	1.6%	3.4%
	Inspiration	3	4.9%	10.3%

	A Way of Thinking	2	3.3%	6.9%
	New Combinations or Synthesis	6	9.8%	20.7%
	Talent	3	4.9%	10.3%
	Out of Ordinary	1	1.6%	3.4%
	Unusual	1	1.6%	3.4%
	Novel	1	1.6%	3.4%
	Manipulation of Factors	1	1.6%	3.4%
	Taking Risks	1	1.6%	3.4%
	Never Done Before	1	1.6%	3.4%
Total		61	100.0%	210.3%

(a) Dichotomy group tabulated at value 1.

Table 3.4 Creativity catchphrases frequencies

3.4.2 Techniques that stimulate creative design thinking

Various creative design thinking techniques and tools have been addressed in the literature survey. The objective of this precise section was to explore the tools used by designers in their design process and how they relate to the ones addressed in the literature. Various creative thinking techniques have been encountered; the results of those techniques are presented in tables 3.5, 3.6 with their frequency of occurrence.

	Cases					
	Valid		Missing		Total	
	N	Percent %	N	Percent %	N	Percent %
Creative Techniques(a)	30	100.0%	0	.0%	30	100.0%

(a) Dichotomy group tabulated at value 1.

Table 3.5 Creative techniques case summary

		Responses		Percent of Cases %
		N	Percent %	
Creative Design Techniques(a)	Search and Widening Knowledge	25	18.8%	83.3%
	Brainstorming Technique	13	9.8%	43.3%
	Analogy Technique	5	3.8%	16.7%
	Combination Technique	1	.8%	3.3%
	Evolution Technique	1	.8%	3.3%
	Emergence	3	2.3%	10.0%
	Concept Mapping	9	6.8%	30.0%
	Collaboration	16	12.0%	53.3%
	Technological Advancements and Visual Tools	24	18.0%	80.0%
	Market and Client Needs Analysis	13	9.8%	43.3%
	Impose Constraints	5	3.8%	16.7%
	Six Hats Roles	3	2.3%	10.0%
	Sample Materials	4	3.0%	13.3%
	Cultural Dimensions	2	1.5%	6.7%
	Experience	4	3.0%	13.3%
	Model making	5	3.8%	16.7%
Total		133	100.0%	443.3%

(a) Dichotomy group tabulated at value 1.

Table 3.6 Creative techniques frequencies

Very low responses with the percentage of 0.8% have been recognized in two techniques namely: combination, and evolution. These exact techniques have been addressed in the literature for their high productivity of creative solutions in various disciplines including design. This result raised an issue about if designers are on familiar terms with these techniques and what they can achieve, or if they use it unconsciously without recognizing its exact terminology. In both cases it has been recognized that the proposed CDT framework should include those specific techniques to familiarize designers with their usefulness and advantages. In addition to those techniques several of the well known

techniques, which were recognized as well for their usefulness in generating creative solutions, have been also incorporated to enhance designers’ familiarity with their design environment.

Higher responses have been addressed relatively in some other techniques such as: search and widening knowledge, technological advancements, collaboration, brainstorming, concept mapping, analogy techniques, and imposing constraints. Although, not all the responses are high enough to say they make a difference, but at least pointed out that they are known among some designers. The results obtained from this section indicated an essential need for such creative techniques to be incorporated in one holistic system to provide a design platform for designers to enhance their creative thinking.

3.4.3 Methods of creative design evaluation

Design evaluation is considered a more systematic and disciplined procedure. The main objective of this procedure is to define the most creative and suitable ideas generated. It can be applied at any stage of the design process. A great deal of creativity is required at this stage for idea screening and selection.

The conducted interviews resulted in multi-criteria for design evaluation. A result of 25 criteria has been summarized in tables 3.7 and 3.8. The most preferable ones were namely: design aesthetics, functionality, achieving objectives, cost, idea uniqueness, likeability, novelty, quality, and cultural values.

	Cases					
	Valid		Missing		Total	
	N	Percent %	N	Percent %	N	Percent %
Evaluation Criteria(a)	29	96.7%	1	3.3%	30	100.0%

(a) Dichotomy group tabulated at value 1.

Table 3.7 Evaluation criteria case summary

		Responses		Percent of Cases %
		N	Percent %	
Evaluation Criteria(a)	Design Functionality	9	11.0%	31.0%
	Unique Ideas	6	7.3%	20.7%
	Design Aesthetics	12	14.6%	41.4%
	Design Practicality	1	1.2%	3.4%
	Achieve Objectives	8	9.8%	27.6%
	Design Usability	1	1.2%	3.4%
	Design Simplicity	1	1.2%	3.4%
	Design Compatibility	2	2.4%	6.9%
	Design Cost	7	8.5%	24.1%
	Design Likeability	6	7.3%	20.7%
	Design Usefulness	1	1.2%	3.4%
	Design Novelty	4	4.9%	13.8%
	Design Viability	1	1.2%	3.4%
	Design Mechanism	1	1.2%	3.4%
	Design Cultural Values	4	4.9%	13.8%
	Users Feedback	3	3.7%	10.3%
	Design Suitability	2	2.4%	6.9%
	Materials Used	3	3.7%	10.3%
	Design Quality	4	4.9%	13.8%
	Design Efficiency	1	1.2%	3.4%
	Testing Results	1	1.2%	3.4%
	Design Applicability	1	1.2%	3.4%
	Design Context	1	1.2%	3.4%
	Design Complexity	1	1.2%	3.4%
	Manufacturability	1	1.2%	3.4%
Total		82	100.0%	282.8%

(a) Dichotomy group tabulated at value 1.

Table 3.8 Evaluation criteria frequencies

These displayed results can be grouped into two major aspects of evaluation criteria; appropriateness and novelty. An idea is considered creative if it is both appropriate and

novel. It is appropriate if it satisfies the design requirements such as the required functions, behaviours, and structures. On the other hand, it is considered novel if it introduces new functions, behaviours, and/or structures. This classification of design evaluation criteria integrated the gathered criteria from the interviews and classified them into two focused aspects. It provides an efficient way of evaluation especially at the early design stages where the design knowledge is in its abstract form and no detailed knowledge is available at this stage. It can provide a good base for the evaluation procedures in the proposed CDT system.

3.4.4 Design process followed

The analysis of the design processes given by the designers has been categorized into steps: the first, second, third, fourth, fifth, and sixth processes. The processes given by each designer have been ordered in those categories as given by him/her respectively. The following frequency tables and bar charts give an indication of how designers approach a design problem.

In the first process as shown in table 3.9 and figure 3.1, 56.7% of the designers start by defining requirements and objectives of the problem, 23.3% start by widening their knowledge, 16.7% start by designing concepts, while 3.3% start by detailing designs. In the second process as shown in table 3.10 and figure 3.2, 42.9% start by designing concepts, 21.4% by widening their knowledge, 17.9% by defining requirements and objectives of the design problem, 10.7% by developing their ideas, and 7.1% by detailing their designs. In the third process as shown in table 3.11 and figure 3.3, 40% start by designing concepts, 20% by developing their designs, 20% by detailing their designs, 12% by evaluating their designs, and 8% by making models and prototypes. In the fourth process as shown in table 3.12 and figure 3.4, 35.7% start by developing their designs, 28.6% by evaluating their designs, 21.4% by making models and prototypes, and 14.3% by detailing their designs. In the fifth process as shown in table 3.13 and figure 3.5, 42.9% start by detailing their

designs, 28.6% by developing their designs, 14.3% by evaluating their designs and 14.3% by making models and prototypes. In the sixth process as shown in table 3.14 and figure 3.6, 66.7% start by detailing their designs and 33.3% by making models and prototypes.

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Define Requirements and Objectives	17	56.7	56.7	56.7
	Widening Designers Knowledge	7	23.3	23.3	80.0
	Conceptual Design	5	16.7	16.7	96.7
	Detailed Design	1	3.3	3.3	100.0
	Total	30	100.0	100.0	

Table 3.9 1st design process frequencies

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Conceptual Design	12	40.0	42.9	42.9
	Widening Designers Knowledge	6	20.0	21.4	64.3
	Define Requirements and Objectives	5	16.7	17.9	82.1
	Design Development	3	10.0	10.7	92.9
	Detailed Design	2	6.7	7.1	100.0
	Total	28	93.3	100.0	
Missing	00	2	6.7		
Total		30	100.0		

Table 3.10 2nd design process frequencies

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Conceptual Design	10	33.3	40.0	40.0
	Design Development	5	16.7	20.0	60.0
	Detailed Design	5	16.7	20.0	80.0
	Design Evaluation	3	10.0	12.0	92.0
	Model Making & Prototyping	2	6.7	8.0	100.0
	Total	25	83.3	100.0	
Missing	00	5	16.7		
Total		30	100.0		

Table 3.11 3rd design process frequencies

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Design Development	5	16.7	35.7	35.7
	Design Evaluation	4	13.3	28.6	64.3
	Model Making & Prototyping	3	10.0	21.4	85.7
	Detailed Design	2	6.7	14.3	100.0
	Total	14	46.7	100.0	
Missing	00	16	53.3		
Total		30	100.0		

Table 3.12 4th design process frequencies

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Detailed Design	3	10.0	42.9	42.9
	Design Development	2	6.7	28.6	71.4
	Design Evaluation	1	3.3	14.3	85.7
	Model Making & Prototyping	1	3.3	14.3	100.0
	Total	7	23.3	100.0	
Missing	00	23	76.7		
Total		30	100.0		

Table 3.13 5th design process frequencies

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Detailed Design	2	6.7	66.7	66.7
	Model Making & Prototyping	1	3.3	33.3	100.0
	Total	3	10.0	100.0	
Missing	00	27	90.0		
Total		30	100.0		

Table 3.14 6th design process frequencies

After analysing the results of the design process followed by designers, several conclusions have been reached. The most important one was that design process is definitely a nonlinear process; each designer approaches his own design process differently. The proposed design process has been developed based on the information addressed in the literature and supported by the results obtained from the interviews. It has been divided into five major stages namely: preparation stage, concept generation stage, design development stage, design evaluation, and detailed design stage. Through the structure of the proposed CDT framework, the nonlinearity of the design process has been taken into consideration

by providing the designers with a flexible choice to select his/her design process starting from the stage that suits the designer's thinking and the problem situation. More details can be found in chapter four through the discussion of the proposed design modules.

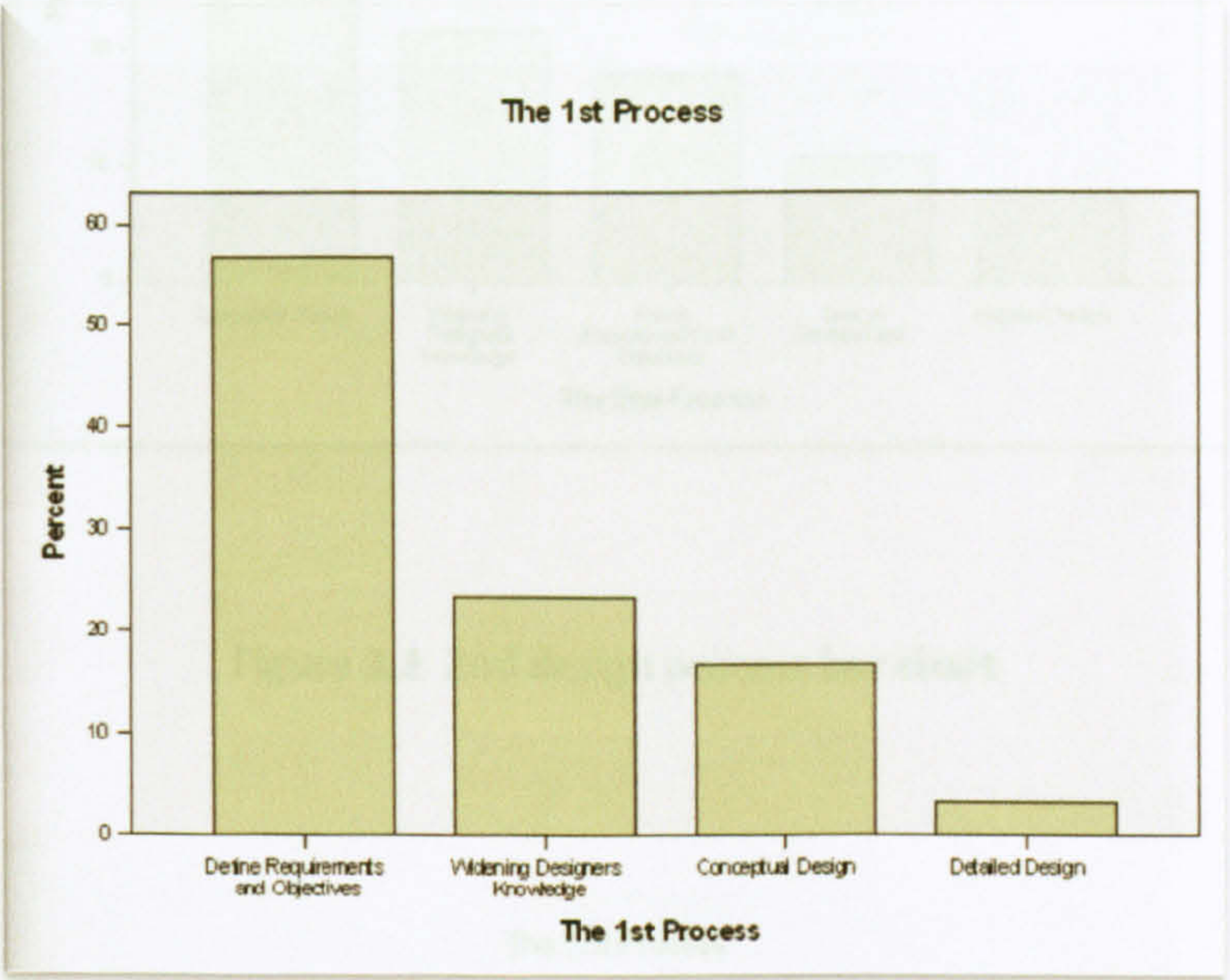


Figure 3.1 1st design process bar chart

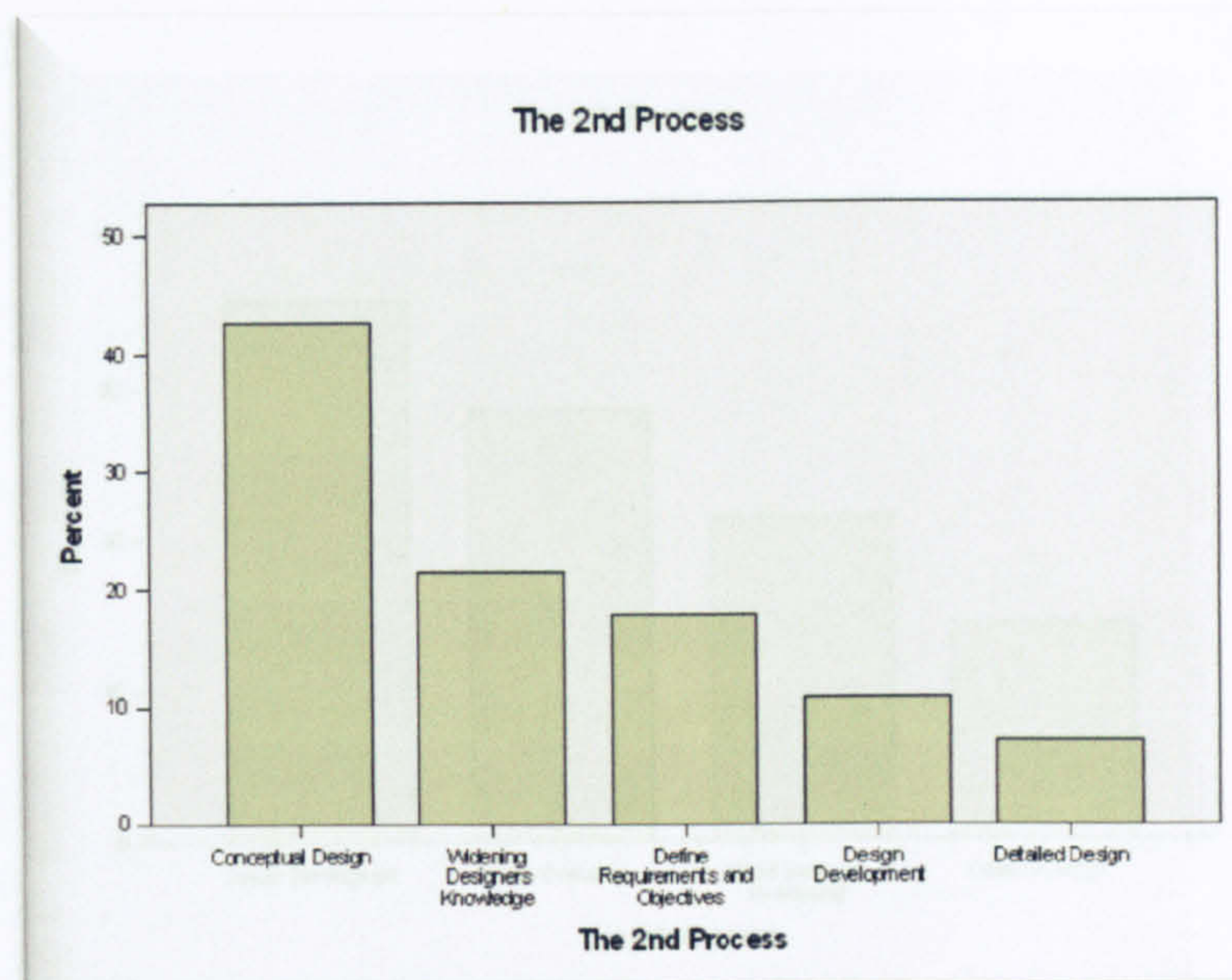


Figure 3.2 2nd design process bar chart

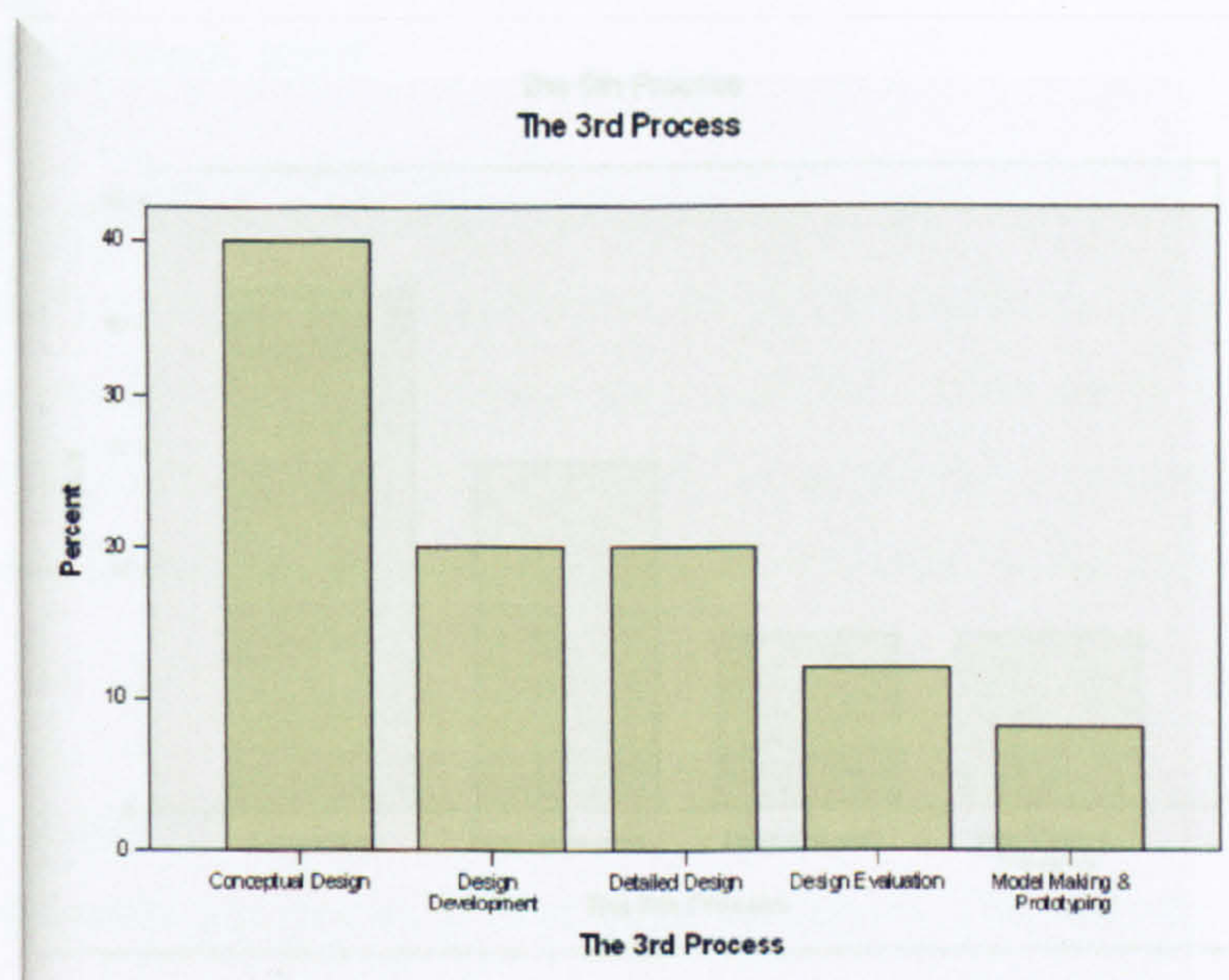


Figure 3.3 3rd design process bar chart

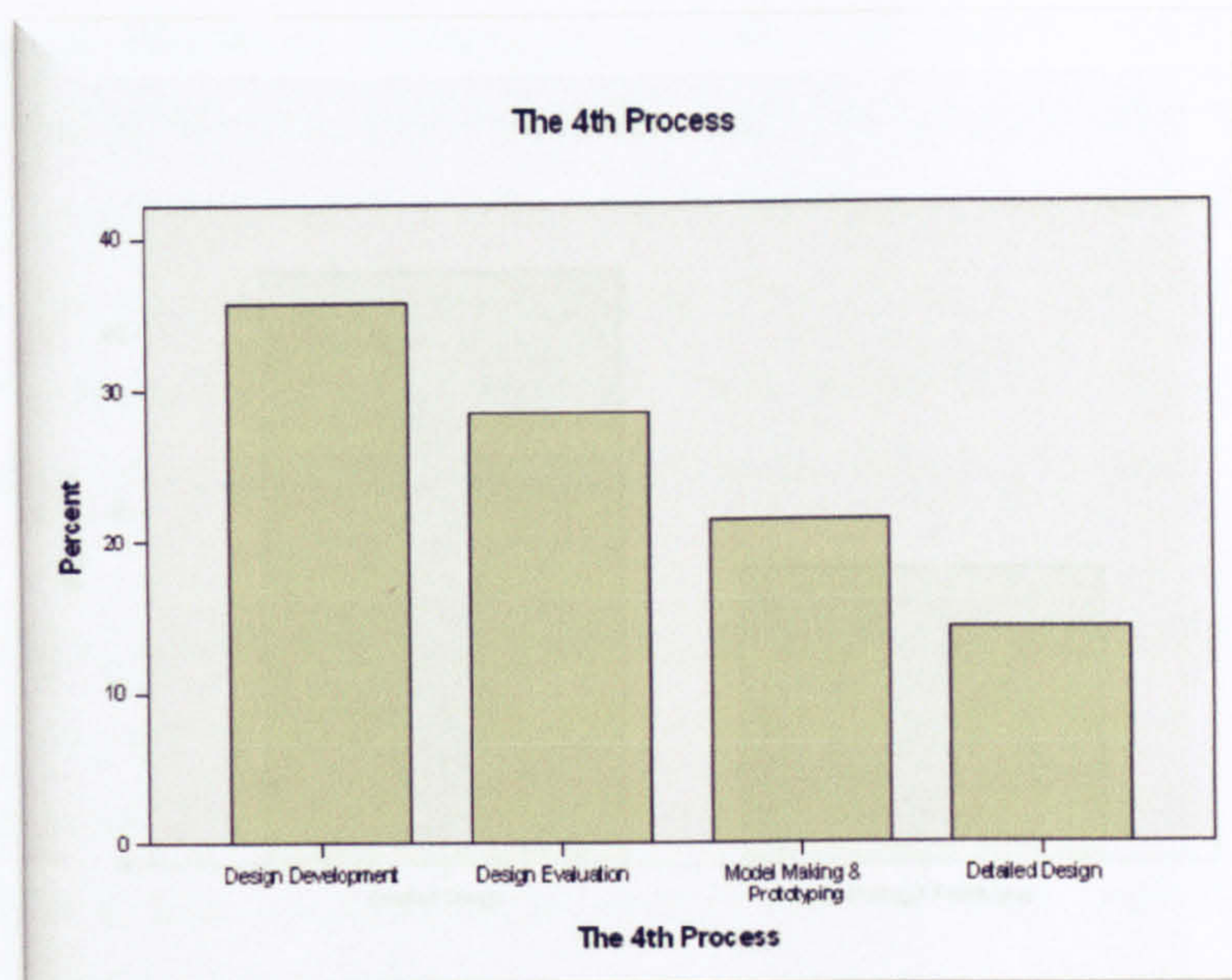


Figure 3.4 4th design process bar chart

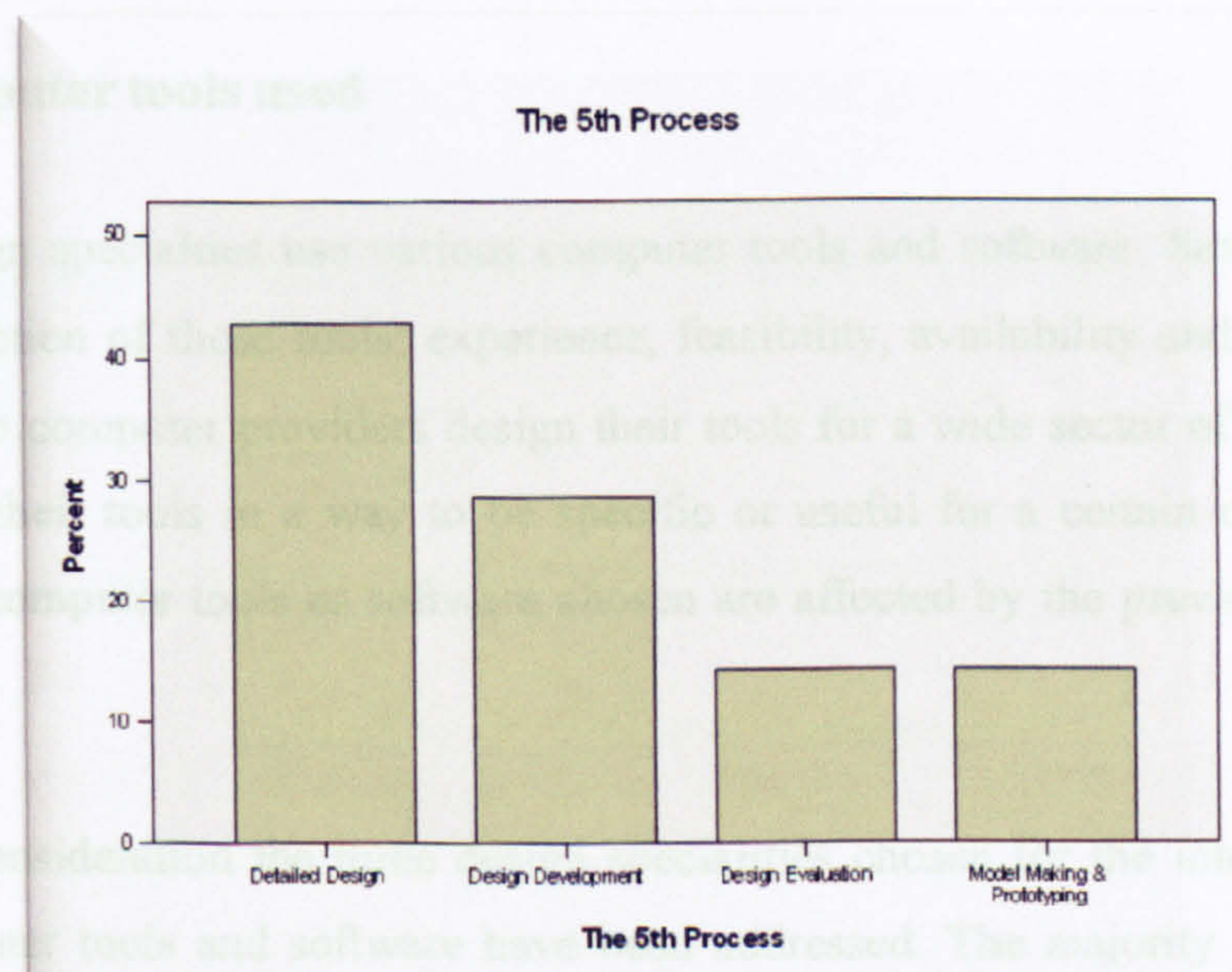


Figure 3.5 5th design process bar chart

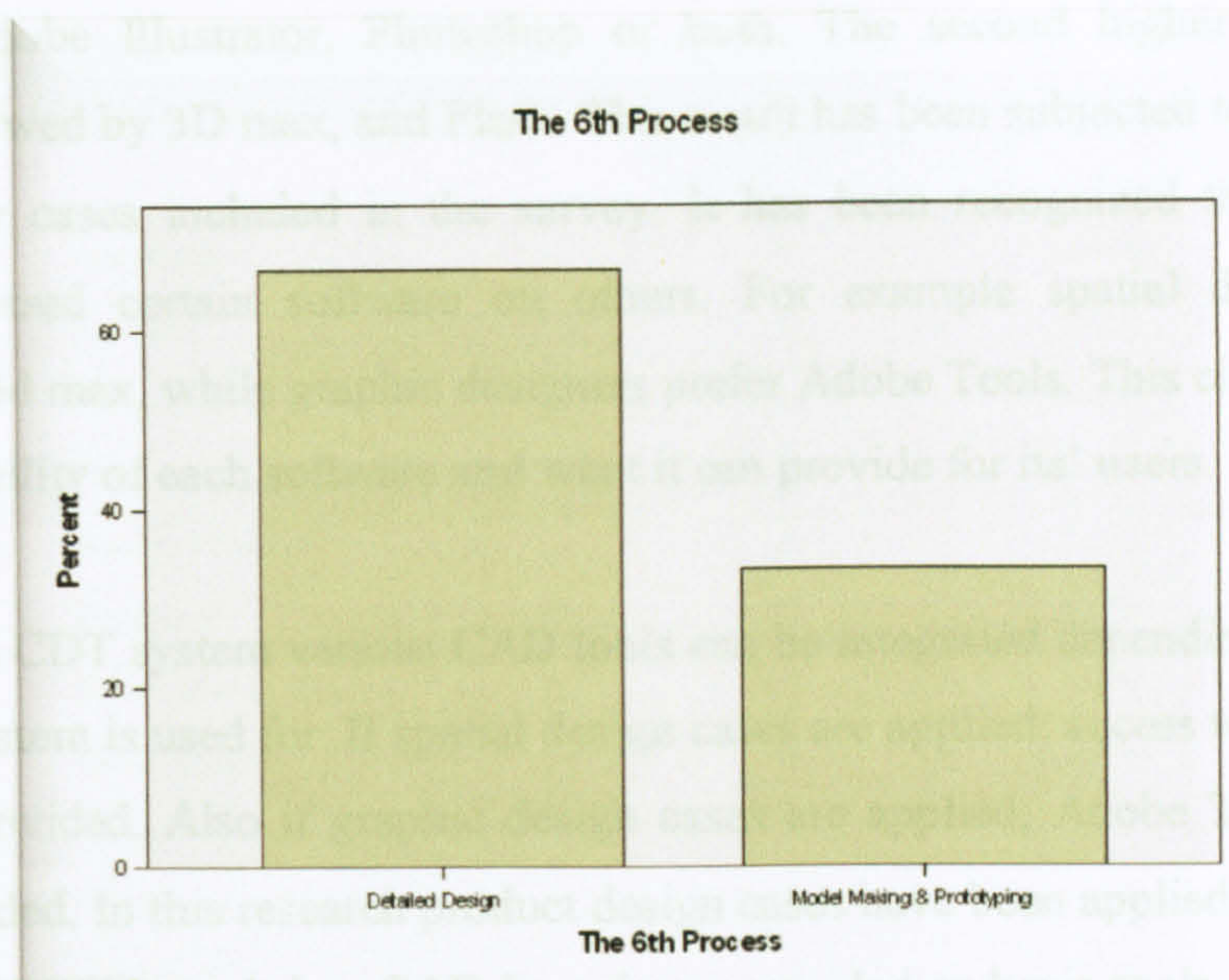


Figure 3.6 6th design process bar chart

3.4.5 Computer tools used

Different design specialties use various computer tools and software. Several factors can affect the selection of those tools; experience, feasibility, availability and convenience of that tool. Some computer providers design their tools for a wide sector of designers while others design their tools in a way to be specific or useful for a certain design sector. In summary the computer tools or software chosen are affected by the previously mentioned factors.

Table 3.15 Computer tools and software

Taking into consideration the three design specialties chosen for the interviews' survey, various computer tools and software have been addressed. The majority of the designers thought of the computer tools as the software they use, excluding any hardware that can be useful to them. 2.1% of the responses mentioned scanners, 2.1% mentioned graphic tablets, and another 2.1% mentioned 3D scanning. The highest ratio has been given for the Adobe

tools, either Adobe Illustrator, Photoshop or both. The second higher ratio was for AutoCAD, followed by 3D max, and Flash. This result has been subjected to the number of design specialty cases included in the survey. It has been recognized that each design discipline preferred certain software on others. For example spatial designers prefer AutoCAD and 3d max, while graphic designers prefer Adobe Tools. This classification was due to the capability of each software and what it can provide for its' users.

In the proposed CDT system various CAD tools can be integrated depending on the design specialty the system is used for. If spatial design cases are applied; access to AutoCAD and 3D max are provided. Also if graphic design cases are applied; Adobe Tools, flash, and Maya are provided. In this research product design cases have been applied; therefore Alias Tools, ProENGINEER, and AutoCAD have been provided as basic tools. These provided tools can be changed according to the users' preferences, since their usability is focused on producing design alternatives.

	Cases					
	Valid		Missing		Total	
	N	Percent %	N	Percent %	N	Percent %
Computer Tools(A)	20	66.7%	10	33.3%	30	100.0%

(a) Dichotomy group tabulated at value 1.

Table 3.15 Computer tools case summary

		Responses		Percent of Cases %
		N	Percent %	
Computer Tools(a)	AutoCAD	7	14.9%	35.0%
	3D Max	6	12.8%	30.0%
	Adobe Tools	13	27.7%	65.0%
	Flash	5	10.6%	25.0%
	Dream Weaver	1	2.1%	5.0%
	Premiere	2	4.3%	10.0%
	After Effect	1	2.1%	5.0%
	Corel Draw	2	4.3%	10.0%
	Maya	2	4.3%	10.0%
	Alias Studio Tools	3	6.4%	15.0%
	Scanners	1	2.1%	5.0%
	Sound Design Programs	1	2.1%	5.0%
	Lectra Modaris	1	2.1%	5.0%
	Graphic Tablets	1	2.1%	5.0%
	3D Scanning	1	2.1%	5.0%
Total		47	100.0%	235.0%

(a) Dichotomy group tabulated at value 1.

Table 3.16 Computer tools frequencies

3.4.7 Use of design computational systems

3.4.6 Computers enhance or delay work

This section supported the previous one by showing the percentage of designers that agree

The main objective of this section is mainly to identify the percentage of designers who believe computers can enhance their work. This issue is considered very essential in such computational systems taking into consideration that designers use computers early in their design process. A high percentage of 90% responses believed that computers enhance their work, while a 10% believed that computers delay their work as shown in tables 3.17 and 3.18. This result gave an indication that such systems are to be used by a high ratio of designers. This is the main aim behind such systems; to attract a large number of designers to use them in order to enhance their creative thinking and productivity.

	Cases					
	Valid		Missing		Total	
	N	Percent %	N	Percent %	N	Percent %
Agree(a)	27	90.0%	3	10.0%	30	100.0%

(a) Dichotomy group tabulated at value 1.

Table 3.17 Computers enhancements of design work agree (case) summary

		Responses		Percent of Cases %
		N	Percent %	
Agree Computers Enhance Work(a)	Computers Enhance Work	27	90.0%	100.0%
	Computers Delay Work	3	10.0%	11.1%
Total		30	100.0%	111.1%

(a) Dichotomy group tabulated at value 1.

Table 3.18 Computers enhancement of design work (agree) frequencies

3.4.7 Use of design computation systems

This section supported the previous one by showing the percentage of designers that agree and disagree with the usefulness of such design computational systems. The results have been arranged in a scale of 6 answers namely: strongly agree, agree, neutral, no comment, disagree, and strongly disagree. High percentages have been pinpointed in strongly agree and agree scales. This result assisted the one in the previous section by revealing the high percentage of designers who support the use of such systems to enhance their design thinking.

N	Valid	30
	Missing	0

Table 3.19 Design computation system's usefulness statistics

		Frequency	Percent %	Valid Percent %	Cumulative Percent %
Valid	Agree	13	43.3	43.3	43.3
	Strongly Agree	12	40.0	40.0	83.3
	Neutral	2	6.7	6.7	90.0
	No comment	1	3.3	3.3	93.3
	Strongly Disagree	1	3.3	3.3	96.7
	Disagree	1	3.3	3.3	100.0
	Total	30	100.0	100.0	

Table 3.20 Design computation systems' usefulness frequencies

The design environment is considered one of the issues that affect the design process. Designers were asked about the design environment they prefer. Various outputs have been classified and presented in tables 3.21 and 3.22, showing their frequency of occurrence. The highest percentages have been recognized in providing flexible, individual and team design environments. The next percentage has been for less constraints and quiet nice surroundings while some other designers preferred more constraints in their working environment.

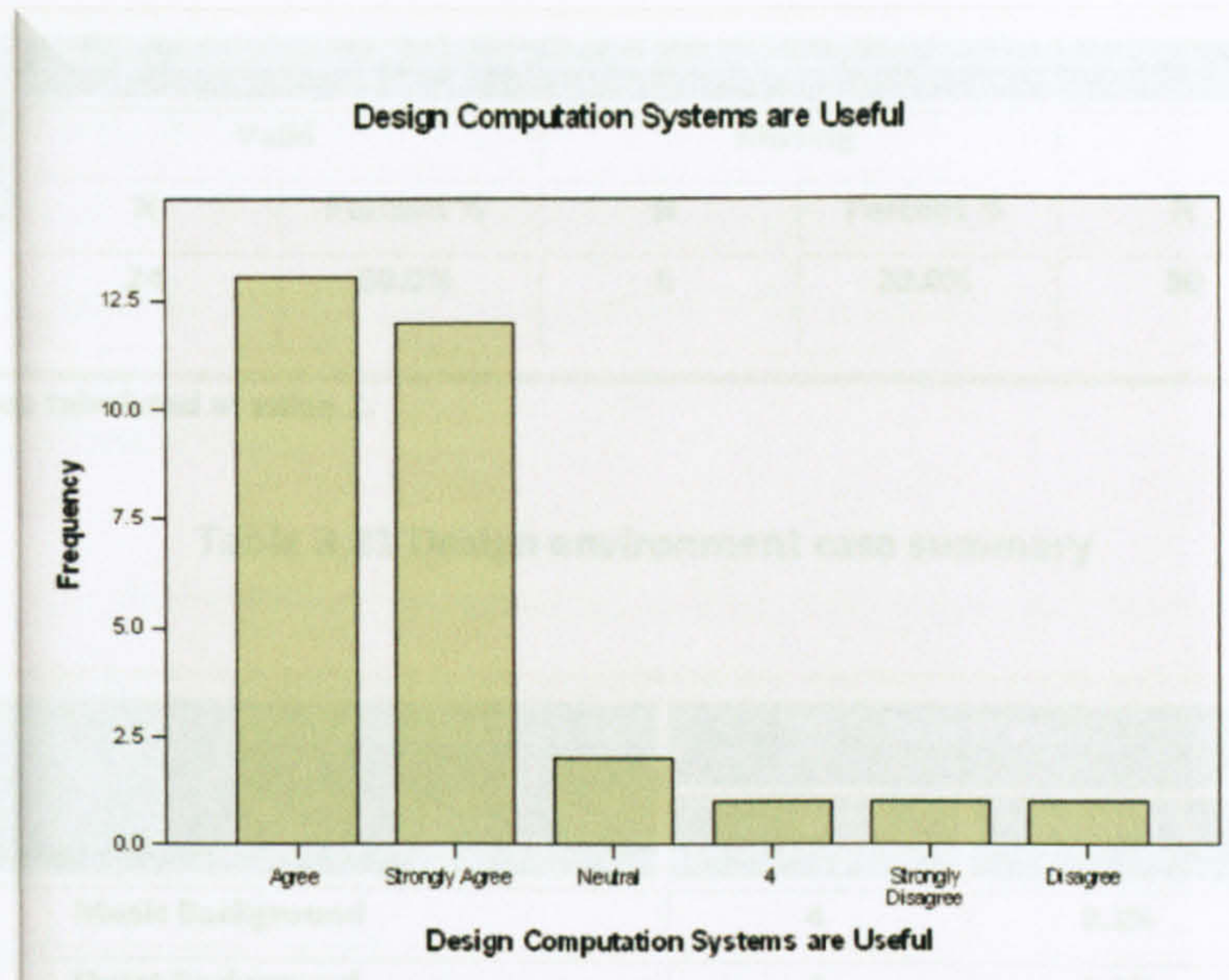


Figure 3.7 Design computation system's usefulness bar chart

3.4.8 Suitable creative design environment

The design environment is considered one of the issues that affect the design process. Designers were asked about the design environment they prefer. Various outputs have been classified and presented in tables 3.21 and 3.22, showing their frequency of occurrence. The highest percentages have been recognized in providing flexible, individual and team design environments. The next percentage has been for less constraints and quiet nice surroundings while some other designers preferred more constraints in their working environment.

	Cases					
	Valid		Missing		Total	
	N	Percent %	N	Percent %	N	Percent %
Environment(a)	24	80.0%	6	20.0%	30	100.0%

(a) Dichotomy group tabulated at value 1.

Table 3.21 Design environment case summary

		Responses		Percent of Cases %
		N	Percent %	
Design Environment(a)	Music Background	4	9.1%	16.7%
	Quiet Background	4	9.1%	16.7%
	Individual Environment	5	11.4%	20.8%
	Team Environment	5	11.4%	20.8%
	Specific Time of the Day	1	2.3%	4.2%
	Physically Comfortable	1	2.3%	4.2%
	Nice Surroundings	2	4.5%	8.3%
	Interactive	2	4.5%	8.3%
	Less Distraction	1	2.3%	4.2%
	Flexibility	5	11.4%	20.8%
	More Constraints	3	6.8%	12.5%
	Less Constraints	4	9.1%	16.7%
	Encouraging Environments	1	2.3%	4.2%
	Dynamic Environments	1	2.3%	4.2%
	Simple Environments	1	2.3%	4.2%
	Full of Inspiration and Motivation	1	2.3%	4.2%
	Relaxed Discussions and Consultations	1	2.3%	4.2%
	Initial Structure to Build on	1	2.3%	4.2%
	User Friendly Environment	1	2.3%	4.2%
Total		44	100.0%	183.3%

(a) Dichotomy group tabulated at value 1.

Table 3.22 Design environment frequencies

- Study the transfer ability of data between the different tools, and the connectivity between a set of specialized tools.

3.5 Summary

In this chapter various issues concerning design practices have been addressed. Several creative design tools and design processes have been classified and presented. The use and perceived significance of such tools and processes has been investigated based on one to one interview survey among designers from various disciplines. The results of the interview survey provided a generic view about design practices among designers and helped in focusing certain issues in structuring the proposed CDT system. They revealed the techniques, processes, evaluation criteria, tools, and environments commonly practiced by designers. Furthermore, they revealed the designer's receptiveness towards the use of computers and computational design systems.

With reference to the creative techniques, it has been verified that some of the techniques were more commonly used among designers than some other ones. The techniques which were not commonly used were addressed in the literature for their high capabilities in supporting creative thinking. Therefore, the proposed CDT system incorporated several creative techniques which have been recognized to be useful in creative thinking; some of them were common among designers while some others have not been considered as common. This variety of tools can provide designers with flexible design environment for generation of new design concepts through exploring different types of techniques and tools.

In relation to design evaluation results, it has been recognized that designers use various multi criteria to evaluate their creative designs. Generic evaluation criteria based on appropriateness and novelty of design concepts has been proposed based on the collected criteria from designers.

In regard to design process results, a clear vision has been established about the nonlinearity of that specific issue. Each designer has his own process to reach design solutions, although, some common guidelines have been recognized. It can be very useful to provide well structured guided procedures for design processes accompanied by flexibility in applying them. This target has been achieved in the proposed CDT system through the incorporation of five design modules; each module represents a different stage of the design process with the necessary procedures and tools. The designers can choose to apply any module of them to create their own design process.

In consideration of computer tools and their enhancement of the design process, it has been acknowledged that computer tools were widely used by designers. The tools they use were related to their design specialty and their personal preference. Furthermore, a high percentage of 90% of the designers believed in using computers to enhance their thinking and design capabilities. Design environments have been identified to be flexible, constrained, and multi-user supported. Therefore, it can be useful to provide designers with flexible design computation systems that can be applied to various design problems, which are user friendly and totally managed by them to create their own design environments.

The usefulness of design computational systems and tools will continue to capture the attention of design researchers, academics and professionals for many years to come. The results obtained from this survey will constitute the base of the CDT framework structure presented in the following chapter.

CHAPTER FOUR

THE PROPOSED FRAMEWORK FOR CREATIVE DESIGN THINKING

4.1 Overview

As illustrated in CHAPTER TWO previous research studies discussed creativity in design and discussed various techniques developed by other authors to enhance creative thinking through the design process. However, those systems were lacking the integration of these techniques using design computational tools and knowledge to support the designer through the different phases of designing. In view of the fact that the future of the design process is heading towards computation; these techniques can be integrated with processes and knowledge through a systematic computerised design system. They can be also improved by using the capabilities of the advanced design computation.

This chapter presents a holistic approach to facilitate and enhance the creative design thinking among designers. The holistic approach involves structured design knowledge, creative tools, creative processes, individual and collaborative design environments. The proposed system supports the use of creative tools within the various design processes using visualization technologies. It provides flexibility in managing knowledge and using the tools or processes among any design task. Furthermore, its structure facilitates the distributed collaboration among design team members by being able to work on the system and viewing what others have designed simultaneously. The architecture of the proposed CDT system is described in detail in sections 4.3, 4.4, and 4.5.

The proposed framework theme is discussed in section 4.3. Section 4.4 represents the overall architecture of the proposed system and the elements of the different modules that construct the system. Furthermore, section 4.5 explains an example scenario of the proposed system. Finally a summary is given in section 4.6.

4.2 Introduction

The application of proper concepts, tools and methods to enhance creative design thinking can speed the response to the rapid growth in market needs by getting novel and creative ideas in short lead time. Recently, computation is expanding rapidly in this direction, but still more research is needed in this area especially in tackling the issue of creative design thinking from a holistic point of view; taking into consideration the humanistic impact required on design matters and concentrating on the design team as a major part of this view.

A system architecture incorporating several creative design thinking tools within the design process is proposed. Based on previous discussed research work a new vision into the creative design process has been achieved. Different creative useful techniques in the design field have been explored and are to be produced in a comprehensive framework to develop a creative design environment for the new millennium designers.

The proposed system architecture was designed to support designers not to replace them. Trends in design research within the last 30 years are heading towards computation but since the design process incorporates so many aspects to be considered still more research is required to provide more comprehensive and holistic systems. Several issues need to be highlighted and solved regarding design computation. Design representation is one of the major issues in such systems.

Since the aim of developing design tools and techniques to support designers is the main concern of this research, therefore, the proposed system is designed in a designer friendly approach where the tools need to be initiated by the user. The designer input is vital to proceed; his/her evaluation and selection of alternatives are the major inputs for the proposed tools. Furthermore, the design alternatives are developed, finalized, and evaluated by designers not the system. The system is created to provide design team members with more options to consider and enhance their cognition of more creative design alternatives.

4.3 The proposed framework theme

A number of conceptual threads from the domains of design, creativity, computation, and collaboration contributed much in establishing the concepts behind the proposed framework. The main framework theme is based on the recognition of design as being a complex learnt skill which involves exploration, problem formulating, and problem solving to achieve certain goals constrained by boundaries of a specific situation. Two classes of design were discussed by Gero (2000) as shown in figure 4.1: routine designing and non-routine designing. Routine designing usually occurs when all the required knowledge is available, while non-routine designing can be divided into two further groups which are innovative and creative designing. Innovative designing occurs when the space boundaries that constrain the ranges of values is abandoned where unexpected values become possible. Creative designing occurs when one or more new variables are introduced into the design state space which increases the capacity of producing creative designs.

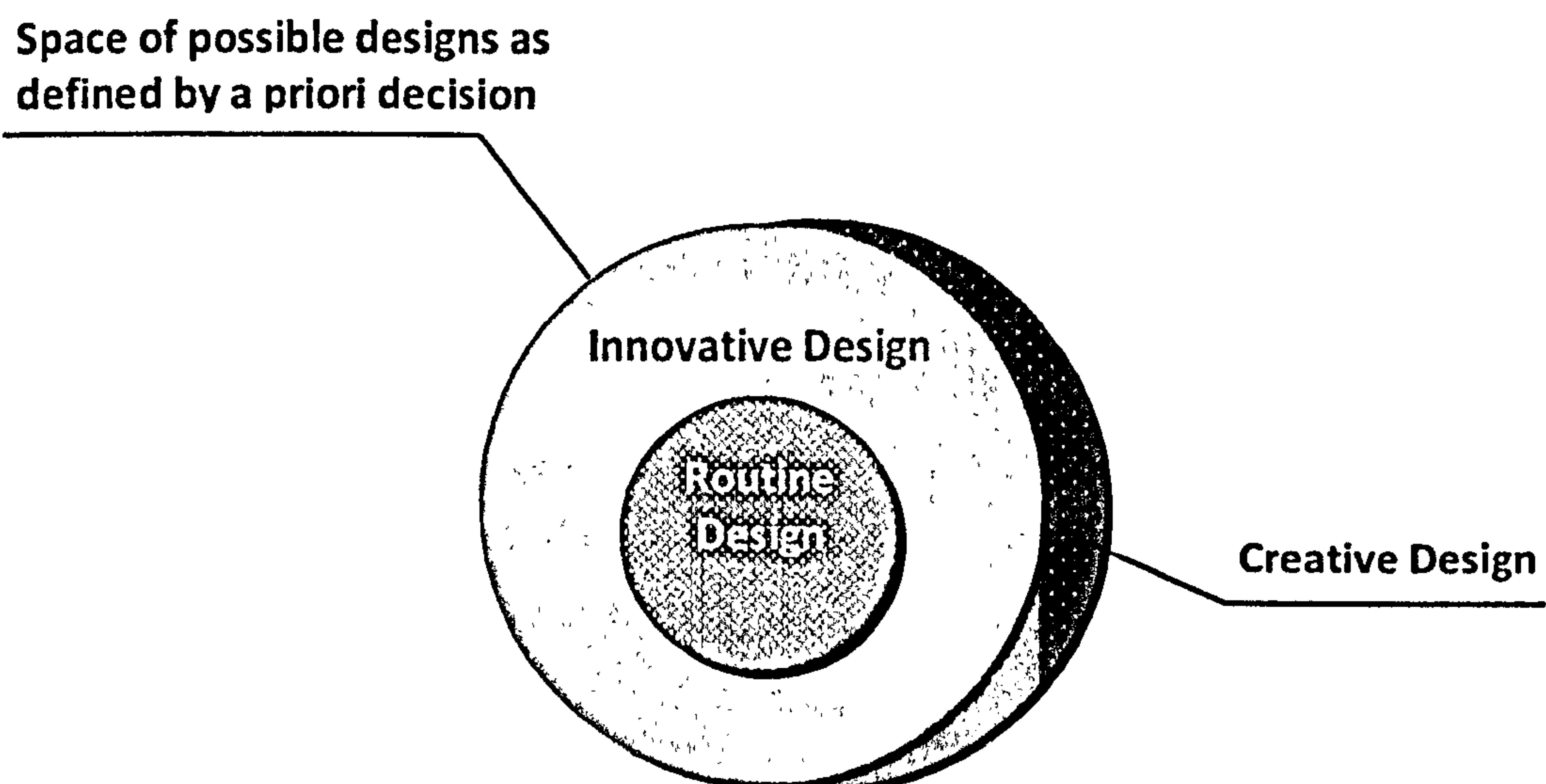


Figure 4.1 Classes of designing, source: (Gero 2000)

The theme of the proposed framework has been developed to facilitate this ability of introducing new variables into the design state space through the interaction between four vital elements for creative design thinking which are: design knowledge, design team,

4.3 The proposed framework theme

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Space of possible designs as defined by a priori decision

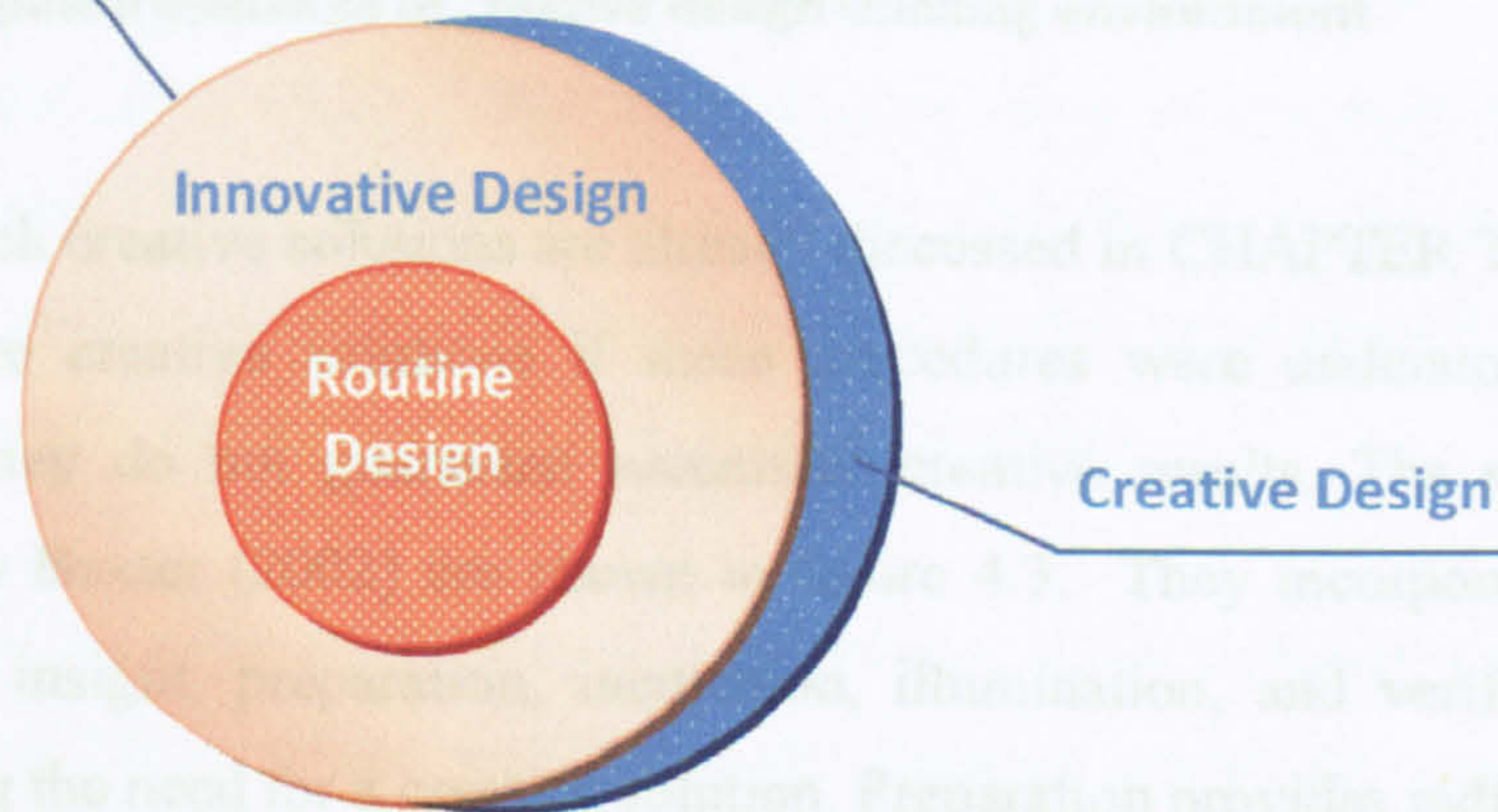


Figure 4.1 Classes of designing, source: (Gero 2000)

The theme of the proposed framework has been developed to facilitate this ability of introducing new variables into the design state space through the interaction between four vital elements for creative design thinking which are: design knowledge, design team,

design processes, and creative tools within a combined design environment as shown in figure 4.2.

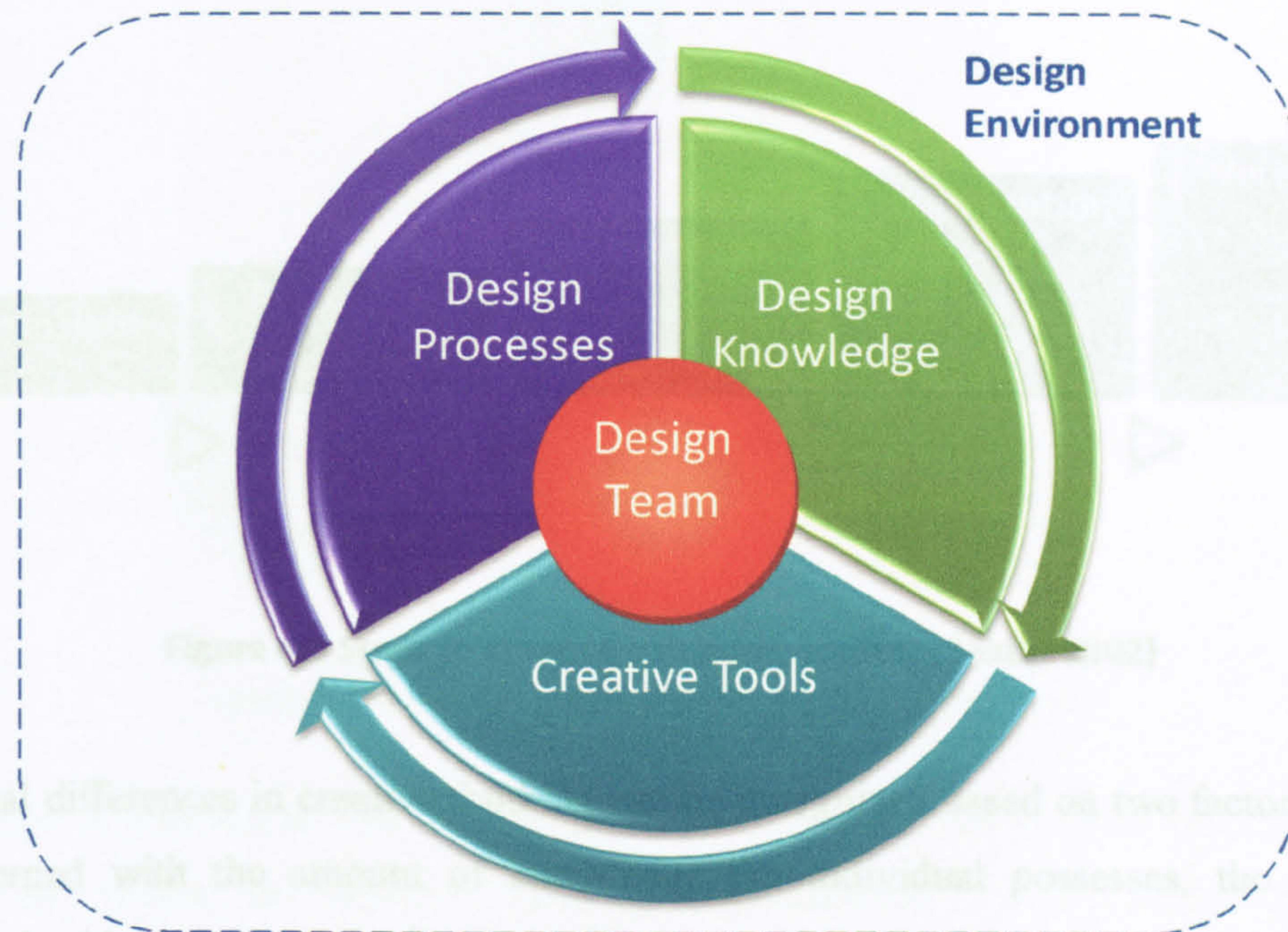


Figure 4.2 Proposed elements of creative design thinking environment

Procedures on how to reach creative solutions are already discussed in CHAPTER TWO. It is more likely to achieve creative solutions if these procedures were understood and implemented, although they do not guarantee successful creative results. The steps to creativity as presented by Baxter (2002) are shown in figure 4.3. They incorporate five procedures namely: first insight, preparation, incubation, illumination, and verification. First insight is recognizing the need for a creative solution. Preparation provides individuals with the opportunity to define and explore the problem under consideration in more depth. It supports designers to identify the problem's boundaries, to set goals, and to absorb relevant knowledge and existing solutions to get a better understanding of all aspects of the problem and existing knowledge. Incubation of ideas is to let them settle in one's mind. Human minds are great devices for association of ideas from past images, experiences, and

thoughts. Incubation and illumination in creative thinking could take long periods of time to take place. Therefore various creative thinking tools and methods can be used to force the human mind to reach a creative solution through lateral thinking.

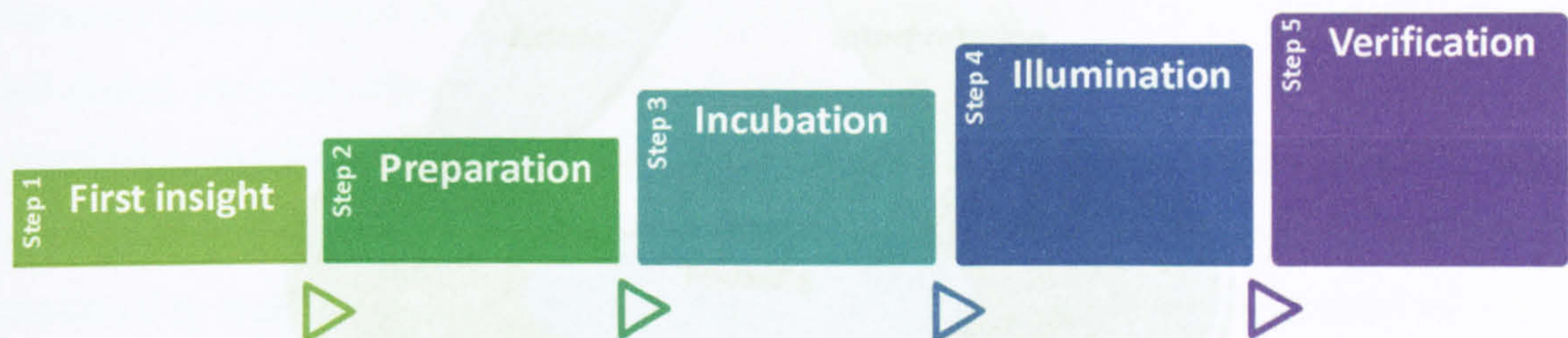


Figure 4.3 Steps to creative solutions, source: (Baxter 2002)

Individual differences in creative thinking can be recognized based on two factors: the first is concerned with the amount of knowledge the individual possesses, the second is concerned with the approach that the individual uses to transform such knowledge. The transformation of knowledge depends on several individual situational issues such as: culture, society, experience, pressures, education, and how these issues encourage or discourage creativity. Therefore, these factors need to be considered in the proposed framework to overcome such individual differences in knowledge possession by being flexible to adapt to various individual situations and design knowledge.

Situatedness in design can be seen as the interaction between three different worlds as shown in figure 4.4 (Gero 2003). These worlds are the external world, the interpreted world, and the expected world. The external world is composed of representations outside the designer's mind. The interpreted world is built inside the designer's mind based on experiences, perceptions, and concepts. The expected world is to be produced by the designer's actions in order to solve the problem. The link between these three worlds is achieved through various processes namely: interpretation, focusing, and action.

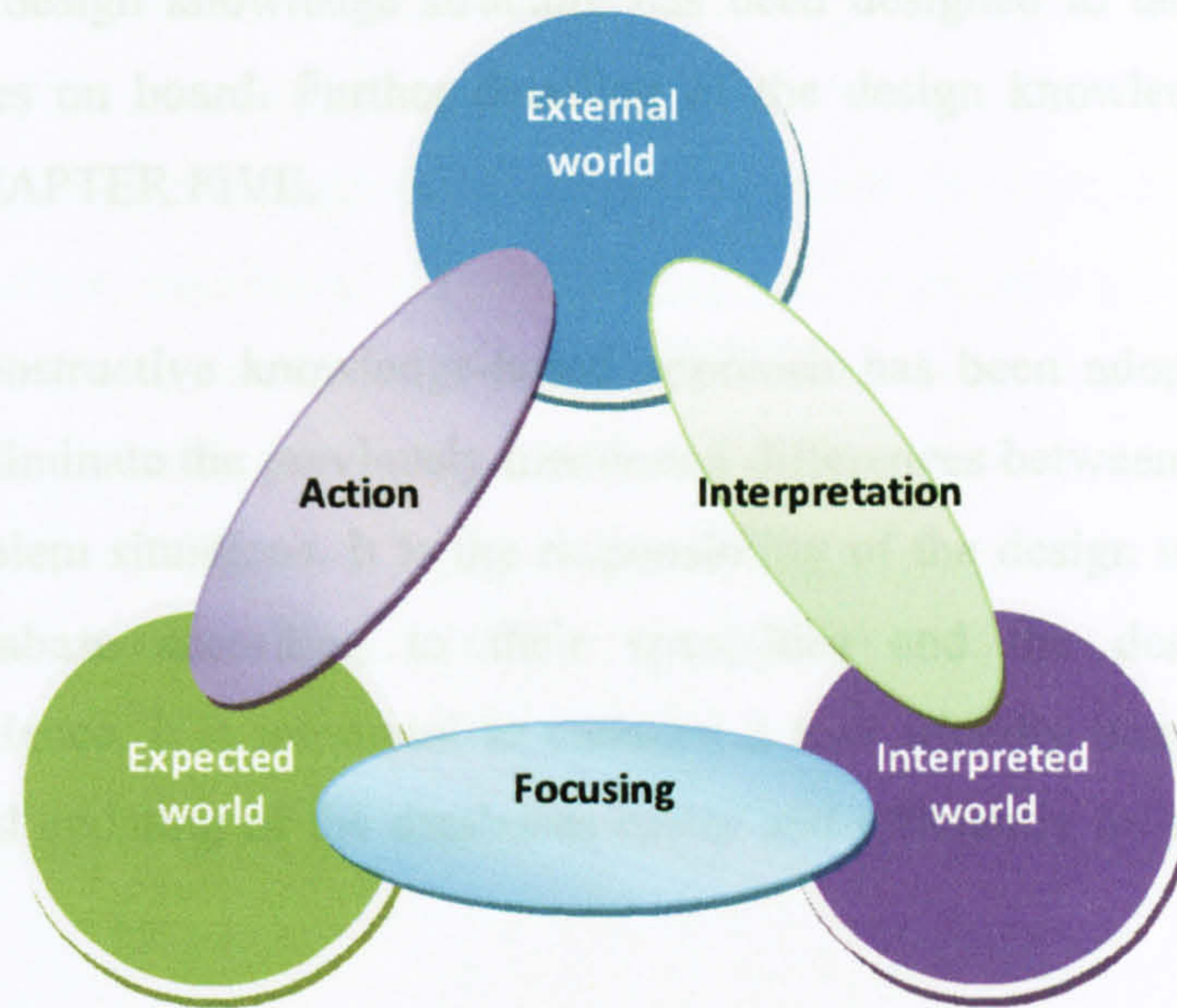


Figure 4.4 Modeling situatedness, source: (Gero, 2003)

Knowledge is considered one of the major elements that has a great emphasis on the success or failure of creative thinking enhancement. Proper design knowledge representation can enforce the creative process towards achieving more creative solutions. Such knowledge needs to be structured carefully to achieve the best results. Proposed design knowledge has been structured in a format to embrace several advantages for both the design team and the incorporated tools and modules taking into consideration several important issues:

- The hierarchical nature of product design solutions.
- The situatedness in design environment where each problem has its own boundaries and requires different types of knowledge.
- The perception of design team members which can be enhanced by supporting visualisation and reasoning of design knowledge.
- The methods and techniques developed in each incorporated creative tool which use design knowledge to perform its procedures.

The developed design knowledge structure has been designed to take all the previously mentioned issues on board. Further detailing of the design knowledge representation is discussed in CHAPTER FIVE.

Therefore, a constructive knowledge-based approach has been adopted in the proposed framework to eliminate the previously mentioned differences between individual designers and design problem situations. It is the responsibility of the design team to construct this knowledge database according to their specialties and the design problem under consideration. Hence, it is important to consider a user friendly interface to facilitate the constructing and updating of the databases easily and efficiently by the authorised design team members.

The design team is considered to be the core of the proposed framework that assures the interaction between knowledge, processes, and tools. The system is worthless without the design team inputs and feedbacks. The main conceptual idea in the proposed framework is to aid creative design thinking among design team members through exposing them to necessary knowledge, and supporting them in generating and exploring new conceptual ideas by incorporating various creative tools and integrating design processes within a flexible design environment.

Various creative thinking tools were discussed in the literature. A number of these tools were selected to be developed and incorporated within the proposed framework. Some of the selected tools were recognised to be familiar among designers as discussed in CHAPTER THREE, and have the capability of being computerised such as brainstorming, concept mapping, and analogy. Some other tools were not recognized as familiar among designers, but still were selected, developed, and incorporated because of their acknowledged usefulness in the production of creative solutions such as combination and evolution.

Design process that makes use of the design knowledge is fundamental to the formulation of creative ideas. Several creative design models were discussed in the literature. Gero and Kannengiesser (2004) proposed the FBS model which includes eight design processes namely: formulation, synthesis, analysis, evaluation, documentation, and three types of reformulation. These processes were conducted on design knowledge representation including function, expected behaviour, structural behaviour, structure, and design description as shown in figure 4.5. The design knowledge representation introduced in the FBS model has been adopted, developed, and incorporated within the proposed CDT system to enhance creative design thinking.

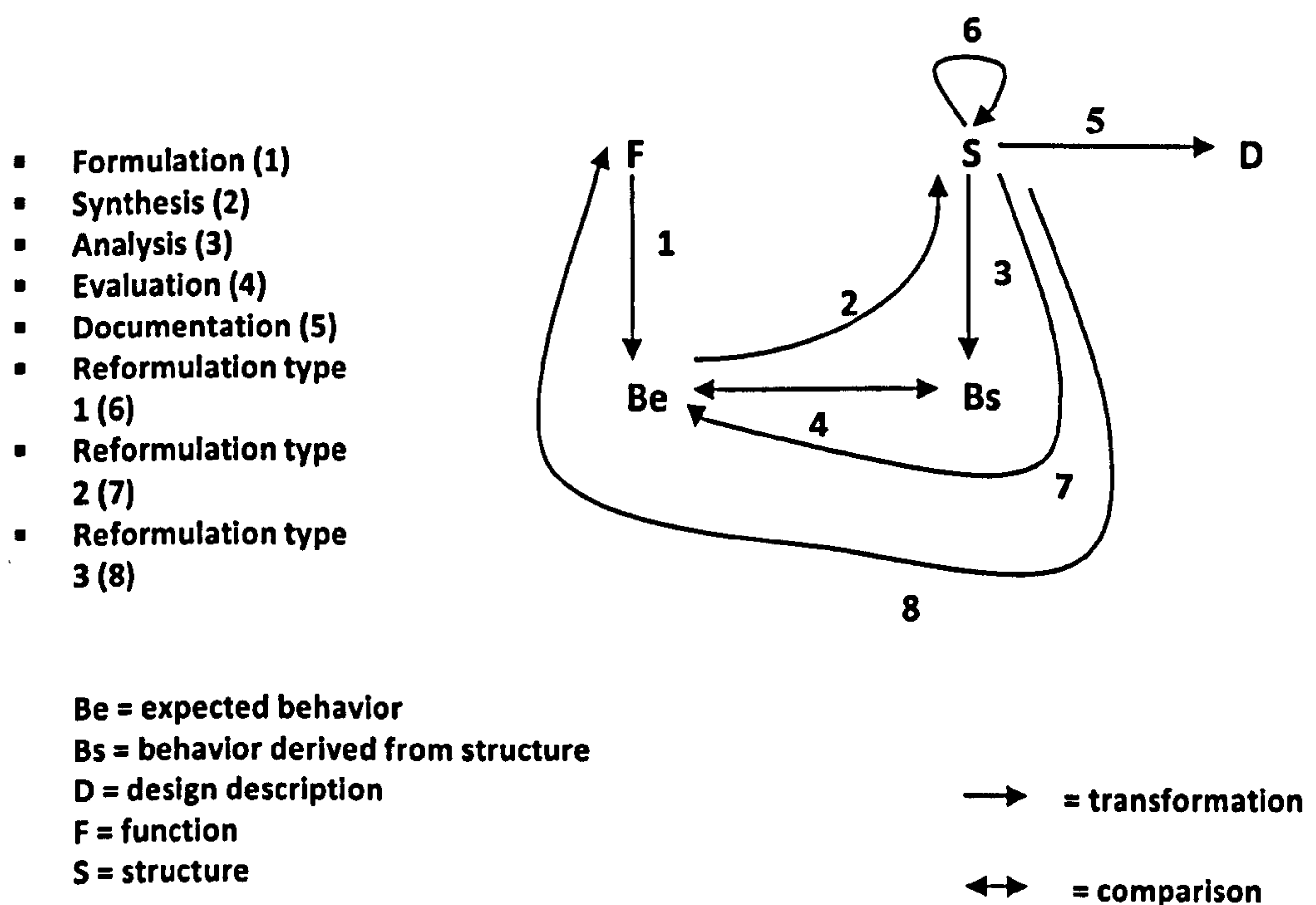


Figure 4.5 Original FBS framework, source: (Gero and Kannengiesser 2004)

Furthermore, Liu (2003) developed the dual generate and test model displayed in figure 4.6. It focused on the interaction between three major elements which are: the individual, the

field, and the domain. The individual represents designers, the field represents society, and the domain represents the source of knowledge. This approach of the interaction between these three domains resembles the previously described concept of situatedness in design through the interaction between the various worlds which can be defined as collaboration.

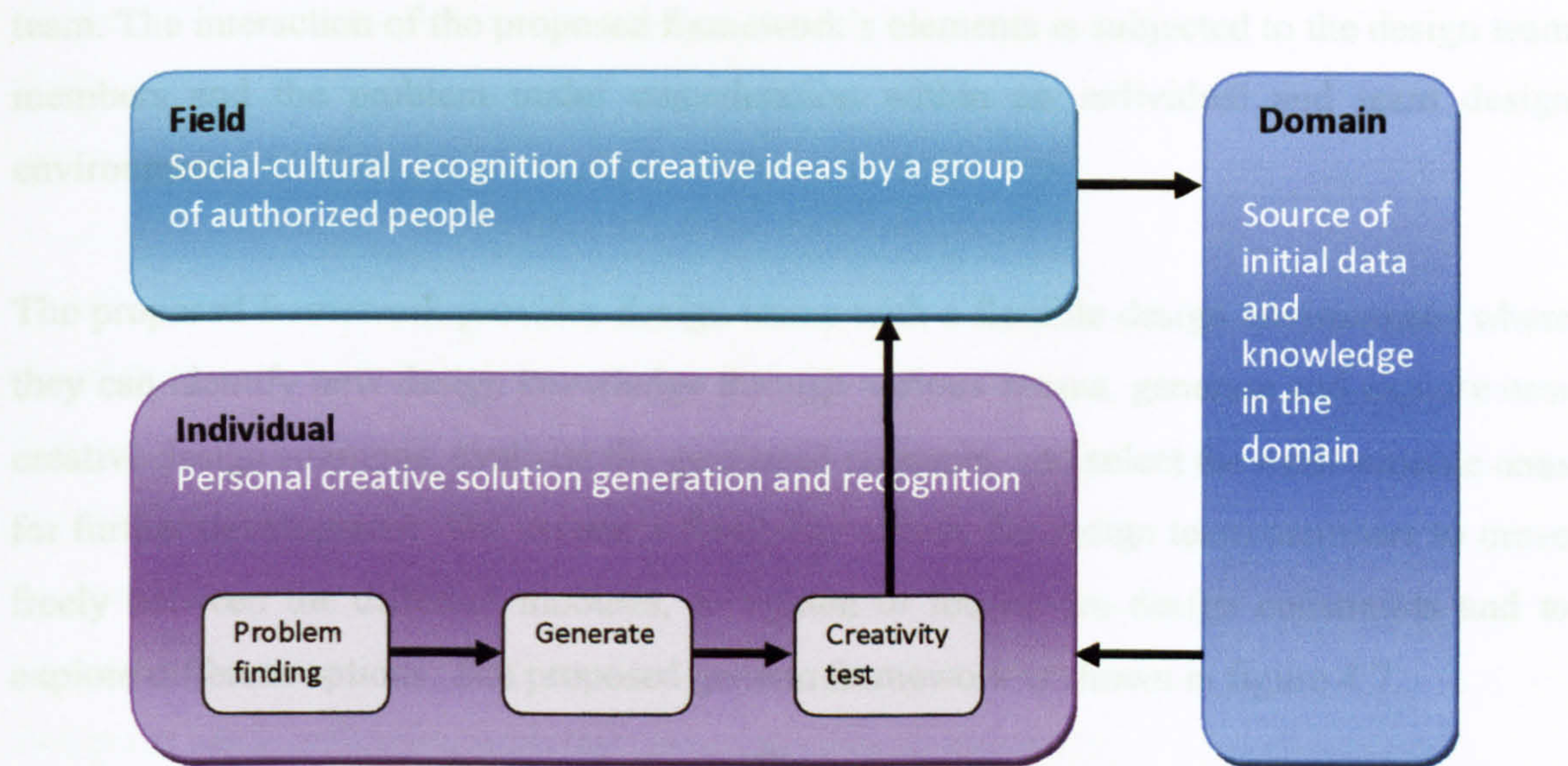


Figure 4.6 Dual generate-and-test model, source: (Liu 2003)

Based on the pre-described design models, a creative-systematic design process has been developed taking into consideration the importance of the early design processes in achieving more creative design solutions through identification of knowledge, formulation of the design problem, and generation of design solutions. Furthermore, flexibility in the design process has been reflected in the proposed framework by allowing the design team to choose the process they want to follow, the tools they prefer to explore, and to identify their own design knowledge which is stored in the system and presented to all authorised users upon request. On the other hand, the interaction between the various elements constituting the proposed CDT system has been achieved through its user design environment, and the incorporated design modules through a user friendly interface.

Figure 4.7 General proposed framework

In summary, the proposed framework composes of knowledge databases, a set of creative design tools, individual and team design environment, a user interface, and five design modules namely: preparation, concept generation, development, evaluation, and detailed design. Each module consists of several processes or techniques to be applied by the design team. The interaction of the proposed framework's elements is subjected to the design team members and the problem under consideration within an individual and team design environment.

The proposed framework provides design teams with a flexible design environment where they can identify new design knowledge through various means, generate and explore new creative design solutions, evaluate the generated concepts, and select the most suitable ones for further development. The system's flexibility allows the design team members to move freely between the different modules, to tighten or loosen the design constraints and to explore different options. The proposed generic framework is shown in figure 4.7.

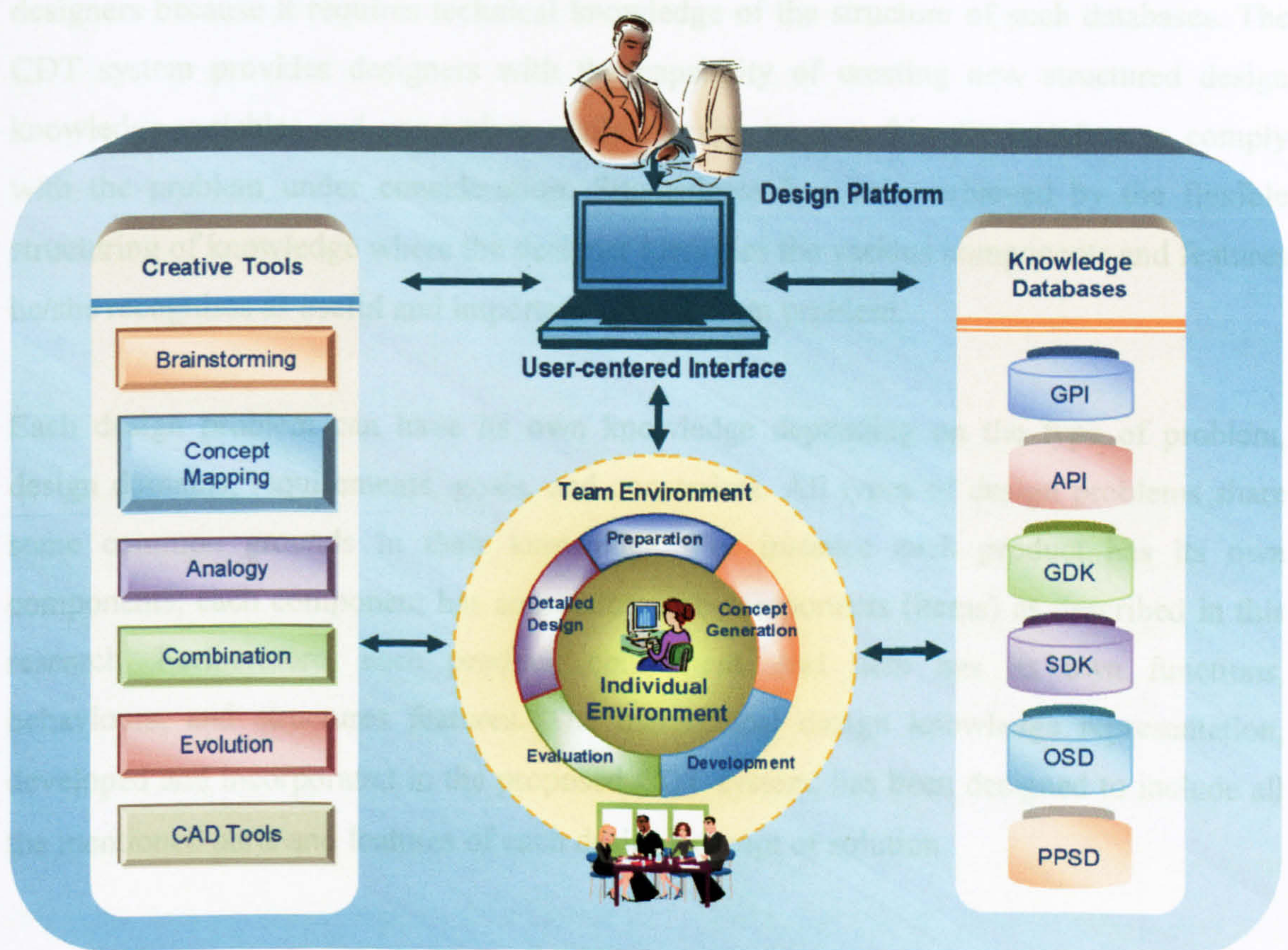


Figure 4.7 Generic proposed framework

4.4 Overall architecture of the proposed system

The proposed architecture has been developed taking into consideration different attributes of well-designed systems such as efficiency, maintainability, reliability and flexibility. The coding and implementing of the system has been achieved by using applications with a high-level graphical environment to develop the different modules of the system and the user-centred interface.

Detailed knowledge databases play an important role in the CDT system. Since the developed system is intended to be used in various design sectors, flexibility in the knowledge incorporated is an important issue. Managing knowledge is provided through the CDT system user interface, to provide accessibility to amend, update, and add new knowledge to the repository which enriches the design environment. This privilege is constrained usually for specialized individuals in data management departments and not designers because it requires technical knowledge of the structure of such databases. The CDT system provides designers with the capability of creating new structured design knowledge variables and constraints easily through its user friendly interface to comply with the problem under consideration. Situatedness has been achieved by the flexible structuring of knowledge where the designer identifies the various components and features he/she recognises as useful and important to the design problem.

Each design problem can have its own knowledge depending on the type of problem, design domains, requirements, goals, and constraints. All types of design problems share some common grounds in their knowledge. For instance each product has its own components; each component has some other sub-components (items) as described in this research. Furthermore, each product, component, and item has its own functions, behaviours, and structures features. The hierarchical design knowledge representation, developed and incorporated in the proposed CDT system, has been designed to include all the mentioned parts and features of each design concept or solution.

Specialized creative tools were incorporated to enhance the designer's thinking and provide the design team with more flexibility to work on the design problem with broader scope of design solution. These tools constitute the major part of the concept generation process, although they can be used at any design process level. Furthermore, CAD tools were integrated with the system to provide drawing and sketching media. Since designers may vary in their CAD practicing capabilities, different sketching media can be used either CAD or manual depending on the designer's skills. Different sketching media were developed recently taking into consideration the designers preferred ways of sketching and the shortcomings of the CAD tools for sketching. The system is flexible to integrate any of them.

Five creative design modules were integrated to represent the design process adopted by most design disciplines with minor changes in some other design sectors. The adopted design process was based on the various models recognized in the literature. Flexibility was an important concern in developing the CDT system, since design process is considered a non-linear practice. The design modules included are preparation, concept generation, development, evaluation, and detailed design. Each module activates specific creative tools to perform its tasks. The architecture of the proposed system is discussed in more detail in the following sections.

4.4.1 Knowledge databases

As pointed out earlier, knowledge and processes that make use of this knowledge are the most fundamental issues from which creative ideas are formed. Providing the designer with the appropriate knowledge for each design task is very important before and through the whole design process. The databases are the source for retrievals of concepts using analogy, combination or evolution tools. Furthermore, the detailed design solutions are stored in those databases to be used in future design problems after the problem is solved. All information related to the design problems are stored in those databases to be referred to at any time. Search that designers usually conduct before any design process also makes use

of the provided knowledge. The proposed knowledge databases for the system are divided into six major areas:

1. **General Project Information (GPI):** contains necessary information about the design projects such as projects' details, requirements, objectives, constraints, and clients' details. It is built by the designers themselves based on meeting with clients, search, and problem formulating.
2. **Active Projects Information (API):** it acts as a working memory where the preliminary created design solutions are stored until they are finalized and approved. It is built by the design team based on the generated ideas using the creative tools such as brainstorming and analogy. The design team can refer to this database whenever necessary. By the end of the project each data is stored in its relative database.
3. **General Design Knowledge (GDK):** contains general design data such as design domains, products, components, items, general behaviours, functions, and structures. This database can be updated using the user friendly interface according to the new situation of the active design project.
4. **Specific Design Knowledge (SDK):** contains specific design knowledge regarding the products' components and specific items for each component. Furthermore, it contains specific functions, behaviours, and structures for each product, component, and item.
5. **Others Sample Designs (OSD):** contains other designers' work where design teams can expand their vision and scope of the design state space to get inspiration or open up new areas to be explored. The constructive representation of the design knowledge is standardized among the various databases using a specific structured scheme.
6. **Previous Projects Sample Designs (PPSD):** contains the already developed projects designed by the design team. After the design problem is solved the solutions are stored in this database as a reference for designers for future work or for amendments. It includes information about the functional, structural, and behavioural aspects of each design project.

4.4.2 Creative Design Thinking Tools

The (CDT) proposed system incorporates various creative design tools which were recognized for their usefulness in producing creative solutions in design problems. These tools constitute a major part of the developed system. Each one of them has its own ways of supporting the design team in their tasks. The major feature they share is their visualization abilities sharing the same representation of design knowledge. The following sections discuss the tools incorporated within the system showing their capabilities and usefulness to the design process.

4.4.2.1 Brainstorming

Brainstorming is a conventional tool for creative thinking based on generating a large number of ideas. It has been addressed in the literature and the interview survey that it is a widely used tool among designers. Its theme is based on generating as many ideas as possible as groups in limited time sessions, where no criticism is allowed and crazy ideas are welcomed. Although in some cases some fixation has been reported where the generated ideas are channelled in one line of thinking and short time sessions produced many shallow ideas where the focus was on quantity not quality. To overcome these shortcomings, the proposed CDT framework developed the brainstorming tool's theme taking into consideration the following issues:

- To provide a variety of procedures to generate ideas namely: brainwriting, brainsketching, and brainrelating without short time limits sessions.
- To generate concepts individually at first without seeing other designers' generated concepts.
- To store the generated concepts in the temporary active project database to review later.
- To share the generated concepts with other designers after the brainstorming sessions have ended.

- To review all the generated concepts and evaluate them by giving them scores based on their appropriateness and novelty.
- To select the most creative concepts and use other incorporated tools to explore more options.

The three mentioned procedures; brainwriting, brainsketching, and brainrelating can be combined or used as a stand alone procedure. The results of brainstorming tool are abstract concepts represented as sketches, descriptions, and relating diagrams. Figure 4.8 displays the procedure followed in using the brainstorming tool.

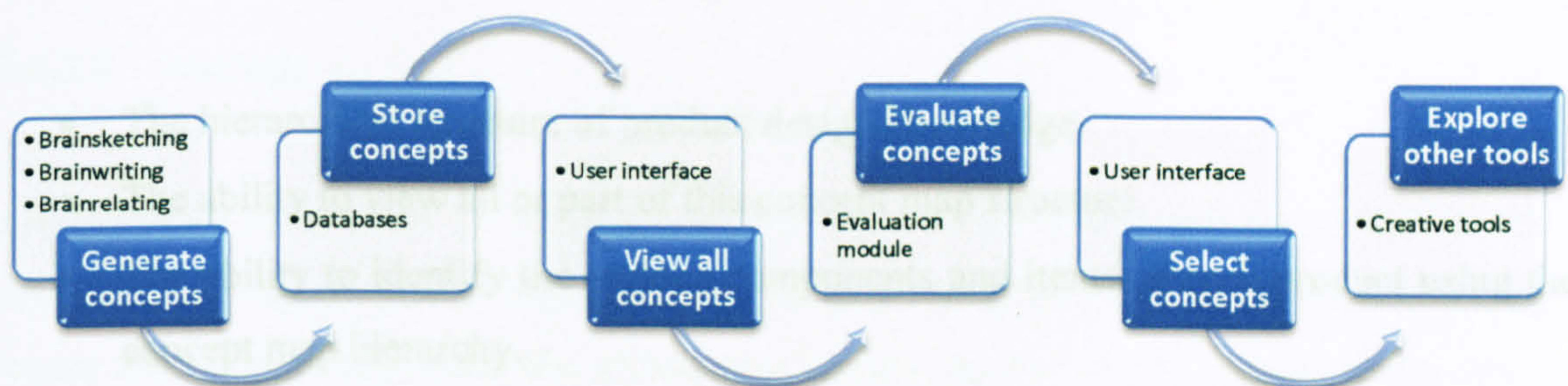


Figure 4.8 Brainstorming tool procedures

4.4.2.2 Concept Mapping

Concept mapping is an externalisation of ones' ideas. The theme behind it is to put all thoughts on one sheet to be able to visualise the different parts of these thoughts easily and at the same time. Since visual perception was recognized to support the design process it will be worthwhile to develop this tool to solve design problems.

This tool was recognized to be very useful in design concept generation as was discussed by several previous research projects (Anderson and Abdalla 2002; Tseng 2004). It is used

to help the designers focus their ways of thinking taking into consideration the different parts of the design problem and to help them restructure their own ideas in a more systematic way which can enhance their creative thinking.

Concept mapping tool, in the proposed CDT system, has been developed to satisfy the visual needs developed in other previous research as well as to structure the design knowledge of the problem. Each generated concept has its own structure and details. This tool provides designers with an interface to structure concepts' knowledge, store it in the databases, and link it to various file types such as images and text files. The procedures of this incorporated tool are shown in figure 4.9. Several issues have been taken into consideration while developing the concept mapping tool:

- The hierarchical structure of product design knowledge.
- The ability to view all or part of this concept map structure.
- The ability to identify the various components and items of each product using the concept map hierarchy.
- The capability to specify functions, behaviours, and structures for each identified component and item of the product.
- The capability to store the generated hierarchical structure of the concept map with all allocated features in the databases to be utilised by other tools and viewed by other design team members.
- The ability to link each part with extra information.

The concept mapping tool has been developed to create new concept maps or retrieve existing ones for review and amendments. The structured design knowledge generated by this tool can be used by other incorporated tools to explore more options.

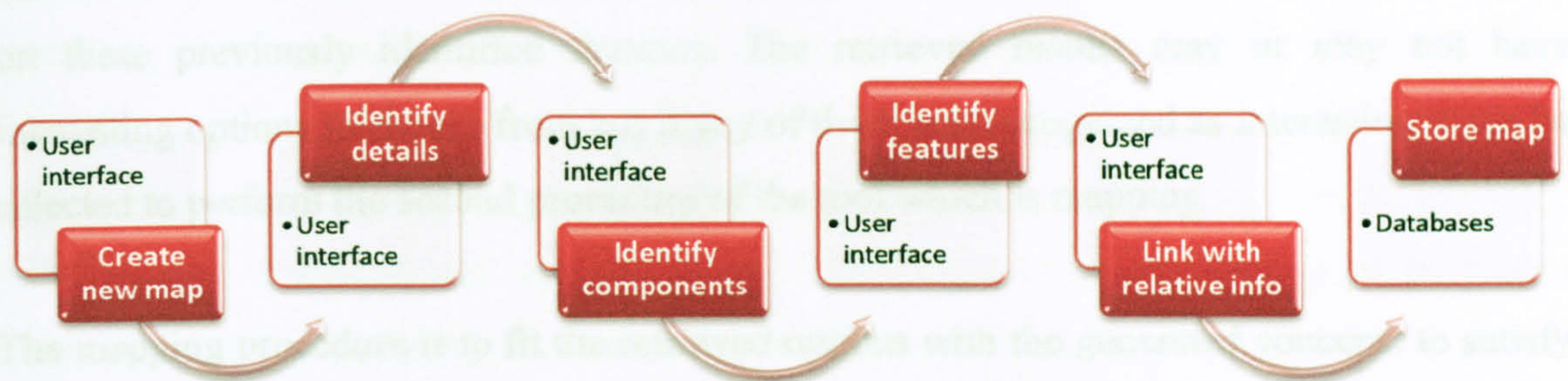


Figure 4.9 Concept mapping tool procedures

4.4.2.3 Analogy

Analogy can be defined as finding solutions applied at similar situations but in other domains. The zipped plastic bag resembles an easy and good example on simple analogy, where the concept of closing the plastic bag using a zipper which is used in the apparel industry is seen as analogy. The idea of the zipper matched the closing function required for the problem and it was combined with the plastic bag after some alterations in the material and the structure of an ordinary zipper to create the zipped plastic bags. Finding analogies in similar situations but from other domains can support the creative thinking of designers by broadening their design solutions space to include other domains which were not considered as useful previously.

An analogy tool has been developed and incorporated in the proposed CDT system to assist designers in exploring more design solutions where emergence of creative ideas can be recognized using analogical recognition of similar situations in other design domains. The developed tool has two main procedures which are: matching and retrieval, and mapping. Matching and retrieval is concerned with searching for solutions that match the existing situation of the problem. The situation of the problem is formed at the early stages of preparation where functions, behaviours, and structures of the problem under consideration

are identified. Therefore, the matching and retrieval of analogical options should be based on these previously identified features. The retrieved results may or may not have interesting options to choose from but if any of them was recognized as interesting it can be selected to perform the second procedure of the tool which is mapping.

The mapping procedure is to fit the retrieved options with the generated concepts to satisfy the design problem's goals, and requirements in that specific situation. The mapping can be conducted at any level in the hierarchical structure of the design concepts. It can be at the component, items, or features' level. The procedures of the developed tool are shown in figures 4.10 and 4.11.

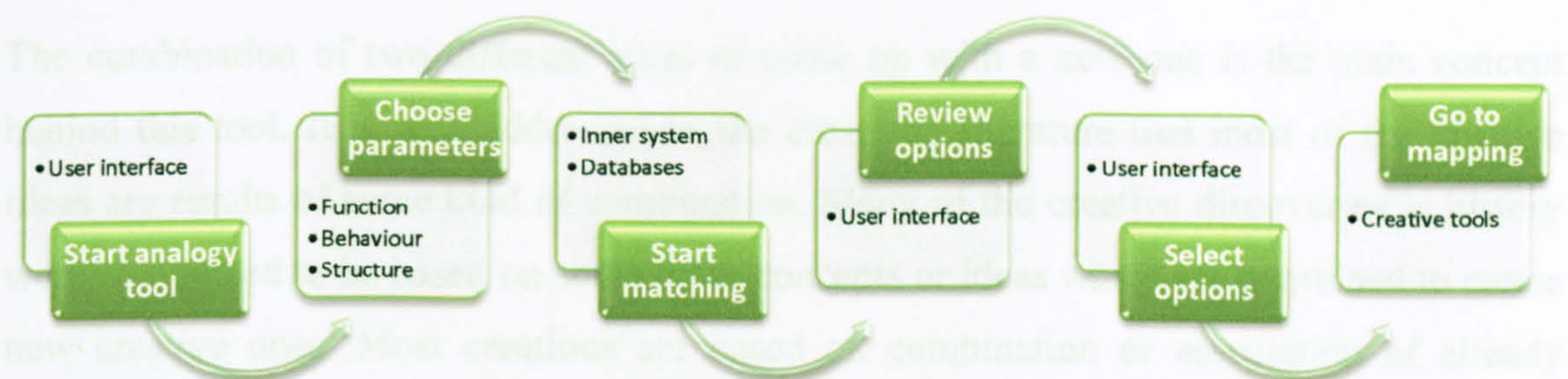


Figure 4.10 Analogy tool (matching and retrieval) procedures

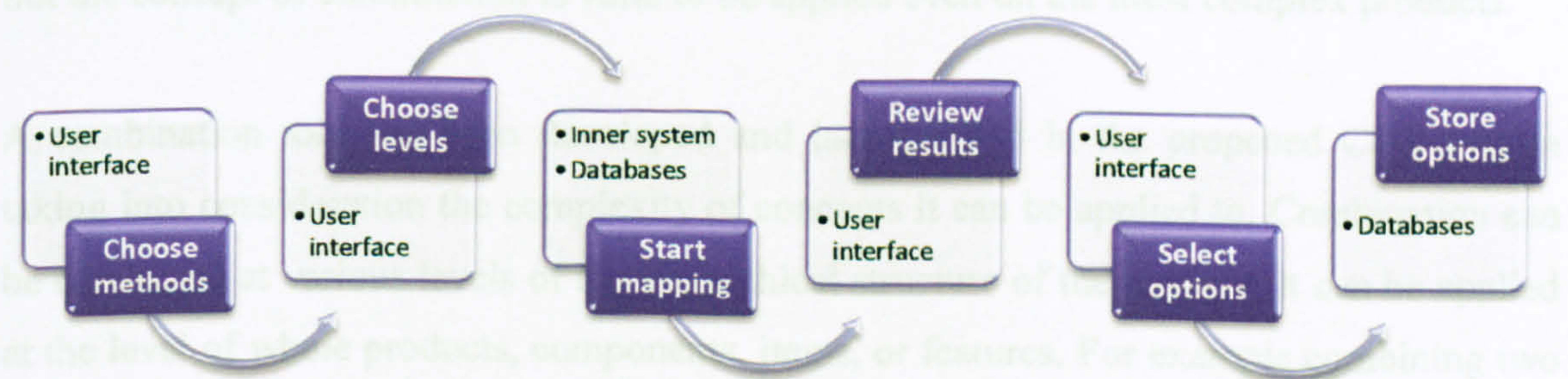


Figure 4.11 Analogy tool (mapping) procedures

In summary analogy tool involves a source state space and a target state space with certain matching and mapping between them to come up with a new concept from an existing one. Mapping can be achieved between structures, functions, or even behaviours among different concepts from the source and the target state spaces. It is used in the proposed CDT system to match and retrieve design knowledge based on analogical parameter imposed by the designer, furthermore, to conduct mapping between the different behavioural, structural, or functional based features. The main aim of analogical tool is the widening of the exploration state space of the design problem.

4.4.2.4 Combination

The combination of two different ideas to come up with a new one is the main concept behind this tool. It is well addressed in the creativity literature that most of the creative ideas are results of some kind of combination. Many of the creative discoveries in history were recognized to be based on some other concepts or ideas which are combined to create new creative ones. Most creations are based on combination or association of already existing solutions. The zipped plastic bag, mentioned earlier for example, combines two already existing ones which are the plastic bag and the zipper. This combination has been achieved after some analogical relation was recognized prior to the combination. Although, this example is very simple in comparison to other complex products in the market now, but the concept of combination is valid to be applied even on the most complex products.

A combination tool has been developed and incorporated in the proposed CDT system taking into consideration the complexity of concepts it can be applied to. Combination can be conducted at various levels of the hierarchical structure of the product. It can be applied at the level of whole products, components, items, or features. For example combining two products such as a coffee maker and a grinder can produce a new product which has the functions of two products installed in one unit. Another example such as a sofa bed combined two functions which are sitting and sleeping. Therefore, the developed

combination tool took this into consideration by providing the designer with the option to choose the combination level he/she is looking for.

Furthermore, four combination methods have been developed and incorporated within the tool to combine options from the newly generated concepts and the already existing ones in the database. These methods are discussed in detail in CHAPTER FIVE. The developed combination tool procedures are displayed in figure 4.12 showing the directed process towards combinational solutions. In summary this tool when computerized can provide designers with more alternatives that have not occurred to them before, which in turn, might trigger a hidden creative idea.

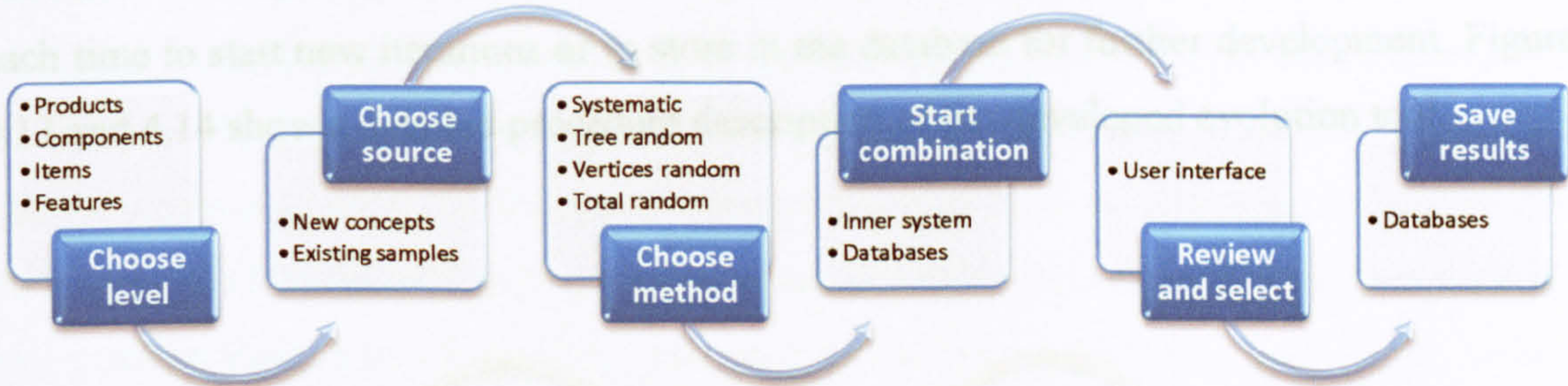


Figure 4.12 Combination tool procedures

4.4.2.5 Evolution

Some research studies discussed evolution and its relation to producing creative solutions. Evolution theme is based on generating new solutions using two or more parents. It usually incorporates two procedures; the first is cross over where different parts of both parents are crossed over between them to create new generations, the second is the mutation where some parts are altered to fit the boundaries of the situation under consideration.

This technique has been developed and incorporated in the proposed CDT system to explore more concepts based on the newly created ones by designers or the solutions already in existence. The two described procedures have been improved to conduct its methods on the developed hierarchical design knowledge representation. Since each concept has its own tree structure, the crossover can be conducted between the branches of various products' trees to generate new options. The cross over procedure can be also conducted at various levels, as described in the previously discussed tools, product, components, items, or features' levels which can be decided by the designers themselves.

The mutation procedure amends or changes the features of the new generations to fit the problem's situation. The mutation amendments can be applied at the function, behaviour, or structures of the generated new solutions. The designers choose the fittest generated options each time to start new iterations or to store in the database for further development. Figure 4.13 and 4.14 show a detailed procedure description of the developed evolution tool.

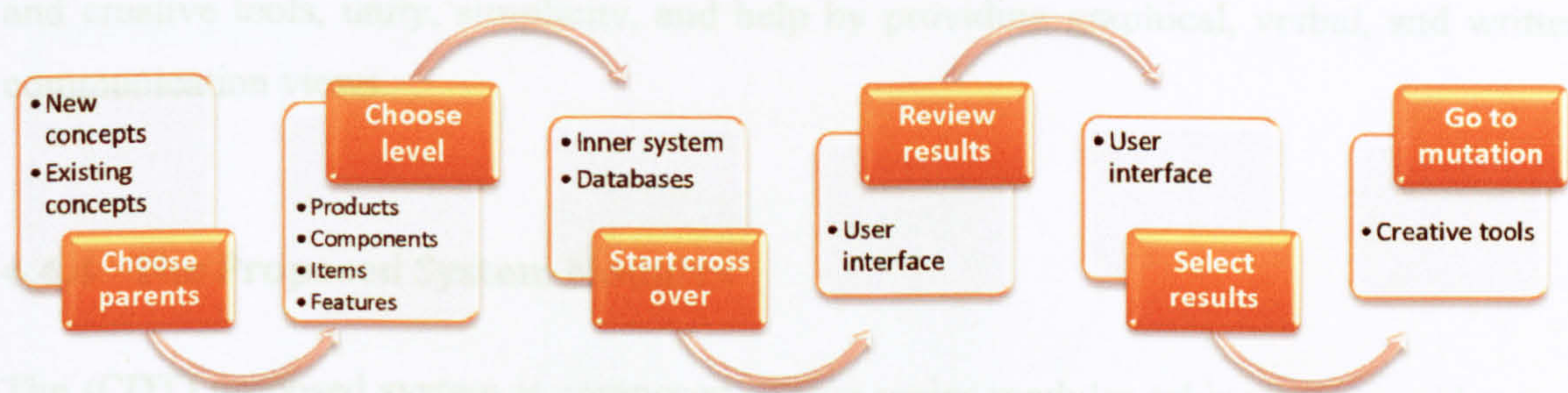


Figure 4.13 Evolution tool (cross over) procedures

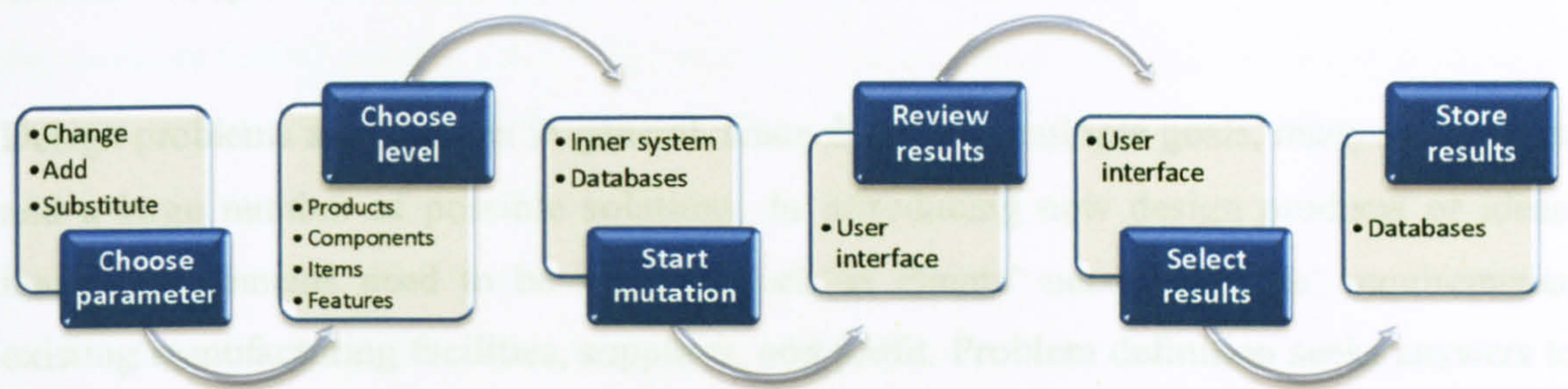


Figure 4.14 Evolution tool (mutation) procedures

4.4.3 User-centred Interface

As mentioned earlier the design team will be the core of the system. Therefore, the design of a user-friendly interface is very crucial in such centred design systems. The interface should provide the users with the most creative, flexible, and easy to handle menus, tools and navigations to facilitate the design process for them, and to save time and effort. The developed CDT interface design guarantees ease of navigation across the different modules and creative tools, unity, simplicity, and help by providing graphical, verbal, and written communication views.

4.4.4 The Proposed System Modules

The (CDT) proposed system is composed of five major modules taking into consideration the systematic design process. Each module of them has several processes to be conducted by the design team and different tools which can assist the design process. The first module is the preparation followed by the module of concept generation. The third one is the development, the fourth is the evaluation, and the fifth one is the detailed design. The design process is known as a non-linear process which has been already revealed in the framework. A more detailed description of the above mentioned modules is given in the following sections.

4.4.4.1 Preparation Module

Design problems are complex in general, since they have multiple goals, many constraints, and a large number of possible solutions. In introducing new design products or ideas, many requirements need to be satisfied such as clients' needs, markets' requirements, existing manufacturing facilities, suppliers, and profit. Problem definition seeks answers to many various questions, which in turn should establish key characteristics of the problem which are: the problem goals, the problem space (requirements), and the problem constraints as shown in figure 4.15.

Exploration of the design problem should provide a wide scope of the design problem under consideration by identifying requirements. Furthermore, the problem definition must specify the problem goals adequately to know when a solution has been reached. It should also define the problem's constraints and limitations.

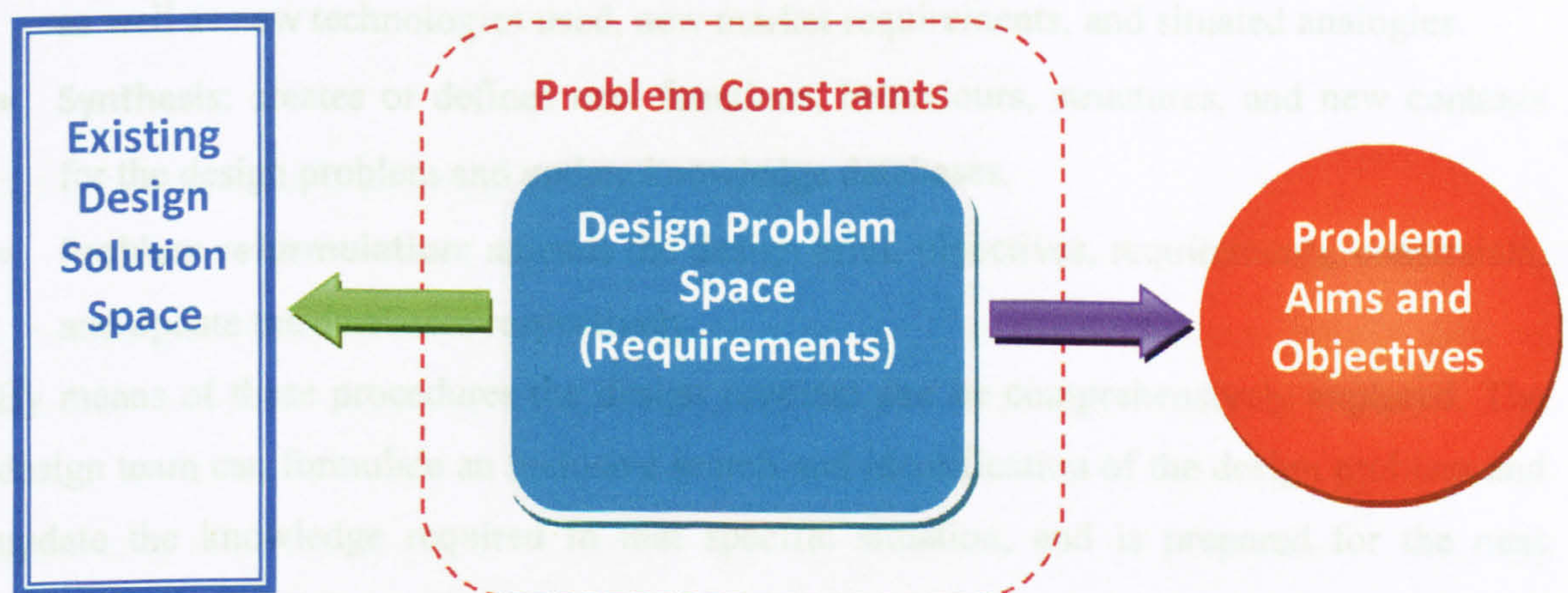


Figure 4.15 Problem characteristics

The proposed preparation module provides essential procedures to explore and define the design problem, specify requirements, and search existing solutions. This module

constitutes the first step in the creative design process concentrating on the importance of the problem formulation in achieving more creative results. It guarantees the search through the different databases available to widen the design team background on the given design problem. Furthermore, it allows the design team to focus on the important issues to be used through the design process and update the knowledge databases according to the design problem under consideration. A generic view of the preparation module issues and procedures is displayed in figure 4.16. This module achieves its purpose through the following procedures:

- **Client's meeting:** establishes a comprehensive background on the client's needs, requirements, likes and dislikes, budget, cultural influences, and limitations.
- **Problem formulation:** defines the aims, objectives, requirements, and constraints based on the client meeting and search conducted by designers.
- **Search:** explores other designers' work, visual images, nature, culture, technical information, and market needs and analysis.
- **Analysis:** analyses the different functions, behaviours, structures of the searched ideas as well as new technologies used, new market requirements, and situated analogies.
- **Synthesis:** creates or defines new functions, behaviours, structures, and new contexts for the design problem and update knowledge databases.
- **Problem reformulation:** amends the design brief, objectives, requirements, constraints, and update the databases respectively.

By means of these procedures the design problem can be comprehensively explored. The design team can formulate an inclusive search and identification of the design problem and update the knowledge required in that specific situation, and is prepared for the next module of concept generation.

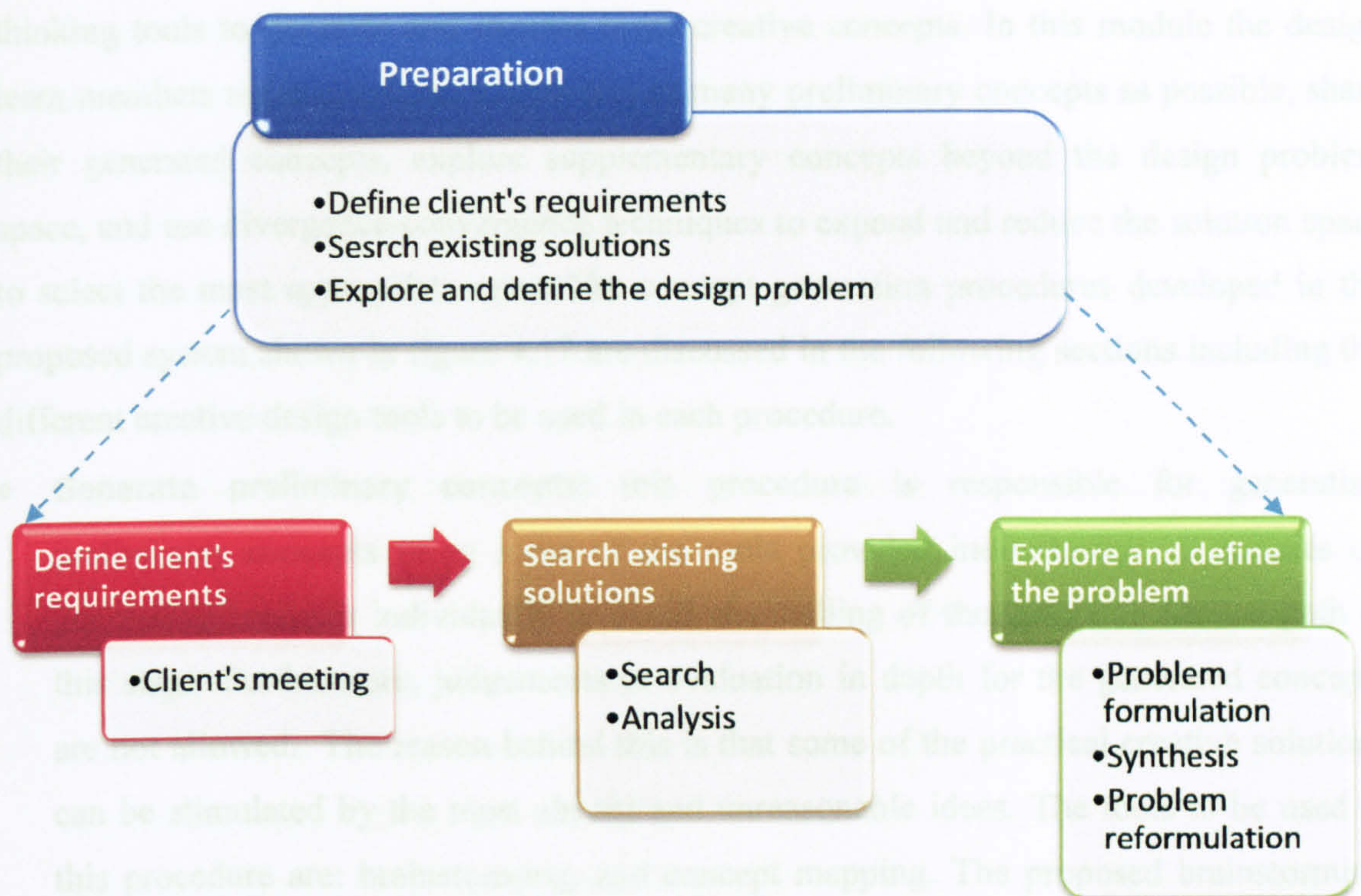


Figure 4.16 Key issues and procedures in the preparation module

4.4.4.2 Concept Generation Module

Concept generation is the core of creative thinking. Various techniques can be used to generate concepts. Some of these techniques require little time and effort, while some others are more complex. A combination of both types of techniques can be useful in generating design concepts from within the boundaries of the design problem, exploring solutions beyond these boundaries, and providing a broad repository of creative tools that can be applied to different design problem situations.

The concept generation module constitutes the heart of the creative thinking in the proposed system, since it activates the application of the different incorporated creative

thinking tools to generate and explore more creative concepts. In this module the design team members are encouraged to generate as many preliminary concepts as possible, share their generated concepts, explore supplementary concepts beyond the design problem space, and use divergence-convergence techniques to expand and reduce the solution space to select the most appropriate ones. The concept generation procedures developed in the proposed system shown in figure 4.17 are discussed in the following sections including the different creative design tools to be used in each procedure.

- **Generate preliminary concepts:** this procedure is responsible for generating preliminary concepts using some of the tools provided individually. It focuses on generating concepts individually to avoid channelling of thoughts in a limited path at this stage. Furthermore, judgements or evaluation in depth for the generated concepts are not allowed. The reason behind this is that some of the practical creative solutions can be stimulated by the most absurd and unreasonable ideas. The tools to be used at this procedure are: brainstorming, and concept mapping. The proposed brainstorming tool integrates three functions to stimulate thinking through concept generation namely, sketching, writing, and relating. The generated concepts are stored in the database to be viewed by other team members at later stages. Concept mapping tool is developed to identify hierarchical tree structures of the generated concepts through previously structured design knowledge representation.
- **Share concepts:** following the generation of a reasonable number of preliminary concepts by all the design team members, designers can view and share their generated concepts. This can be followed by another session of concept generation to create more design solutions based on inspiration of other designers' work. This technique, in sharing the generated concepts after being already generated, assures that lines of thinking are not directed into limited directions by the strongest design team members.
- **Explore supplementary concepts:** this procedure is responsible for exploring more design concepts by utilising the preliminary generated concepts and applying analogy, combination, and evolution tools. It utilises the generated concepts by the design team members, and the stored design solutions already in existence to explore more design concepts based on the designer input. Proposed analogy tool can match and retrieve

design alternatives from the databases based on search parameters defined earlier by the design team such as specific functions, behaviours, and/or structures. Selected options can be mapped to combine or substitute the previously mentioned features to create new variables in the solution space which can be considered creative if it was appropriate. Furthermore, combination and evolution tools utilize the hierarchical concept maps of the generated ideas or existing ones to perform its techniques which are described in detail in CHAPTER FIVE.

- **Organize and display concepts:** after concepts are generated they need to be organized and displayed for selection and further development. This can be achieved by using various visualisation tools such grid views or tree views to display the concepts' hierarchical structure and to facilitate assessment.
- **Select Concepts:** the procedure of selection requires evaluation of the generated abstract concepts to select the most suitable ones based on the criteria of appropriateness and novelty of generated concepts. Afterwards, design development procedures can take place to develop the most appropriate and novel concepts.

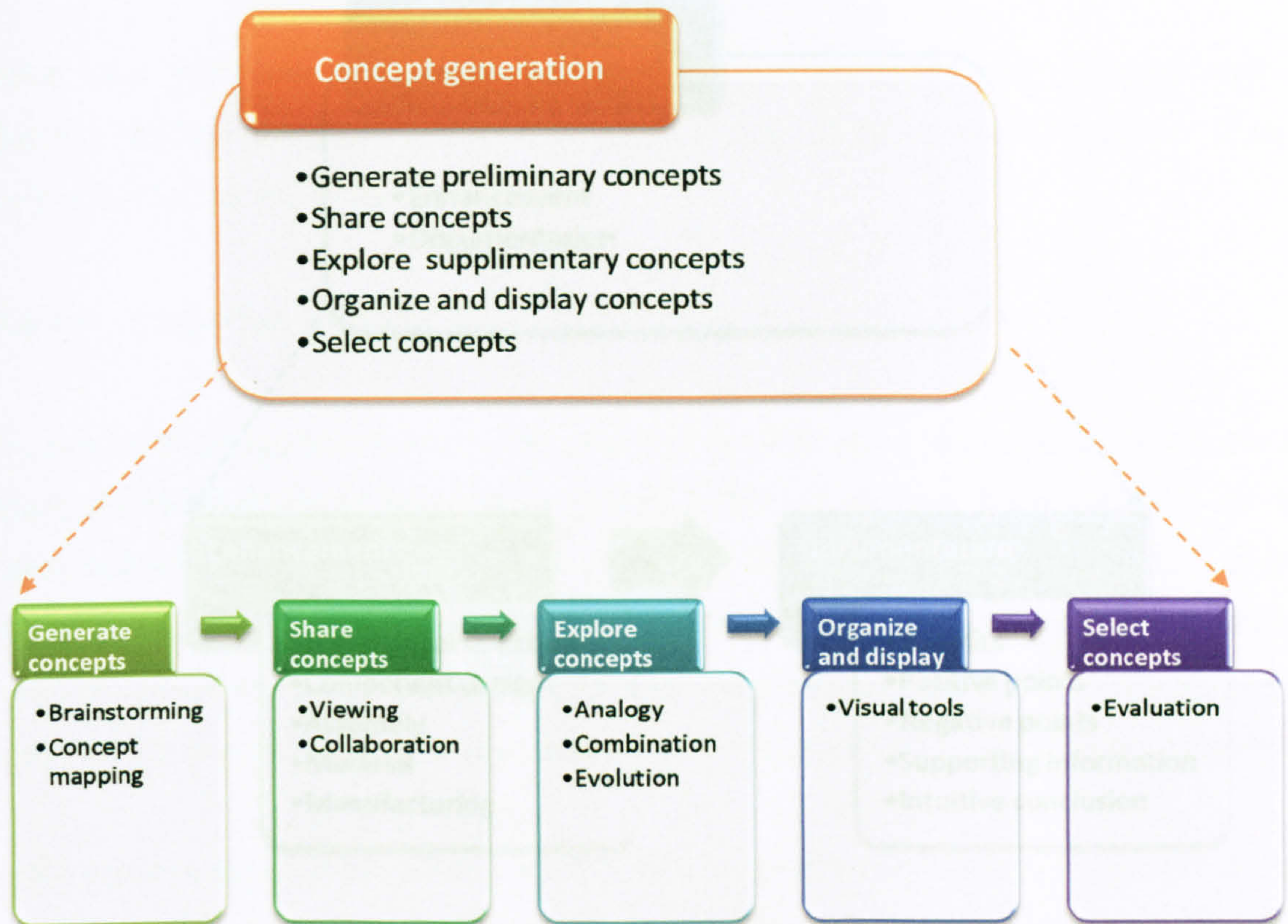


Figure 4.17 Concept generation procedures and tools

4.4.4.3 Development Module

Development of the generated and selected concepts is a further step towards finalising the design of the product. It usually focuses on enhancing the selected concepts taking into consideration various vital issues. This enhancement can be achieved in several section categories such as product hierarchical structure, component design, assembly, material, and manufacturing. This enhancement needs to be documented to present a comprehensive reference for the manufacturing process, future amendments, and the creation of new designs. In the proposed development module two major procedures have been developed namely: enhancement, and documentation as shown in figure 4.18.

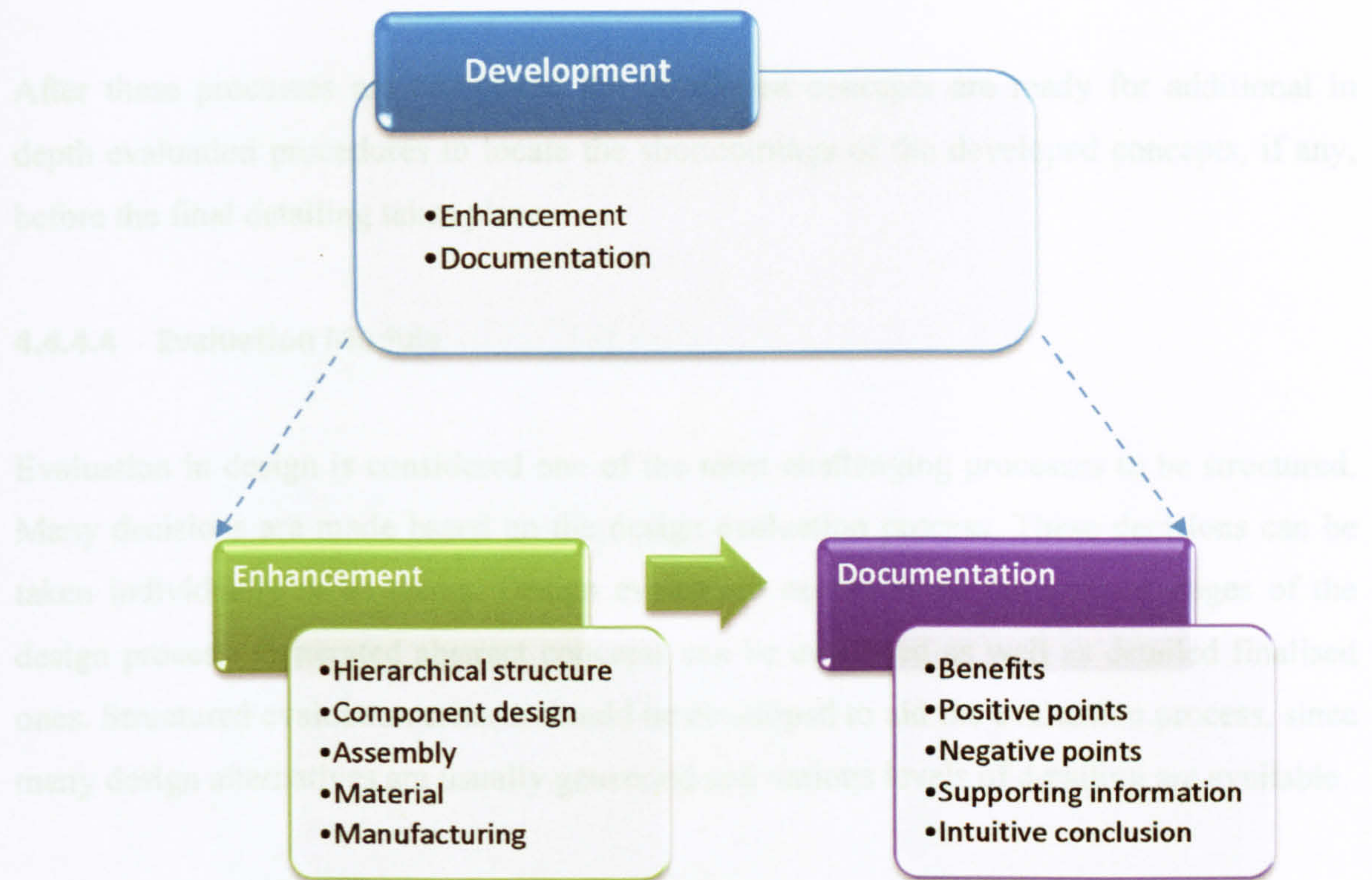


Figure 4.18 Key issues and procedures in the development module

- **Enhancement:** focuses on the improvement of selected concepts from various aspects. Initially the created concept map of the selected idea is revised and amended in more depth and detail because it represents the hierarchical structure of the future new product. Secondly the design team focuses on the design development of the various components of the product to include the new functions, behaviours, and structures created earlier which will, in turn, influence the assembly procedures approved for the manufacturing process. Finally after these enhancements have been approved by the design team they are stored in the databases permanently.
- **Documentation:** constitutes the last process in this module to point out the idea precisely, its benefits, positive points, negatives, potential downsides, supporting information, and intuitive conclusion.

After these processes are completed the developed concepts are ready for additional in depth evaluation procedures to locate the shortcomings of the developed concepts, if any, before the final detailing takes place.

4.4.4.4 Evaluation Module

Evaluation in design is considered one of the most challenging processes to be structured. Many decisions are made based on the design evaluation process. These decisions can be taken individually or as teams. Design evaluation occurs at all the various stages of the design process. Generated abstract concepts can be evaluated as well as detailed finalised ones. Structured evaluation criteria should be developed to aid the evaluation process, since many design alternatives are usually generated and various levels of detailing are available.

In the creative design process early evaluation of the preliminary generated concepts can be useful in saving effort and time. Although the concepts are usually in an abstract form but still can be evaluated to check on their ability to be developed and become new creative solutions for the design problem under consideration.

In this research the evaluation of design concepts has been achieved through three inter-related evaluation modes based on the work of Liu (2000). The first will be at the level of the individual, the second at the level of the design team, and the last will be at the level of society. The interaction between these three levels achieves the design situatedness concept discussed earlier by Gero and Kannengiesser (2004). Figure 4.19 shows the proposed evaluation nested levels implemented in the evaluation module. The first two levels of evaluation are achieved based on multi-dimensional criteria based on appropriateness and novelty of concepts. If the concepts pass the first two levels of evaluation they can be transferred to the final evaluation level by society where different specialties and backgrounds are involved in the evaluation based on a different scope criteria. More detailed explanation of this module's implementation is presented in CHAPTER FIVE.

Office work. Figure 4.20 displays a generic view of the detailed design module showing the various processes and flow.

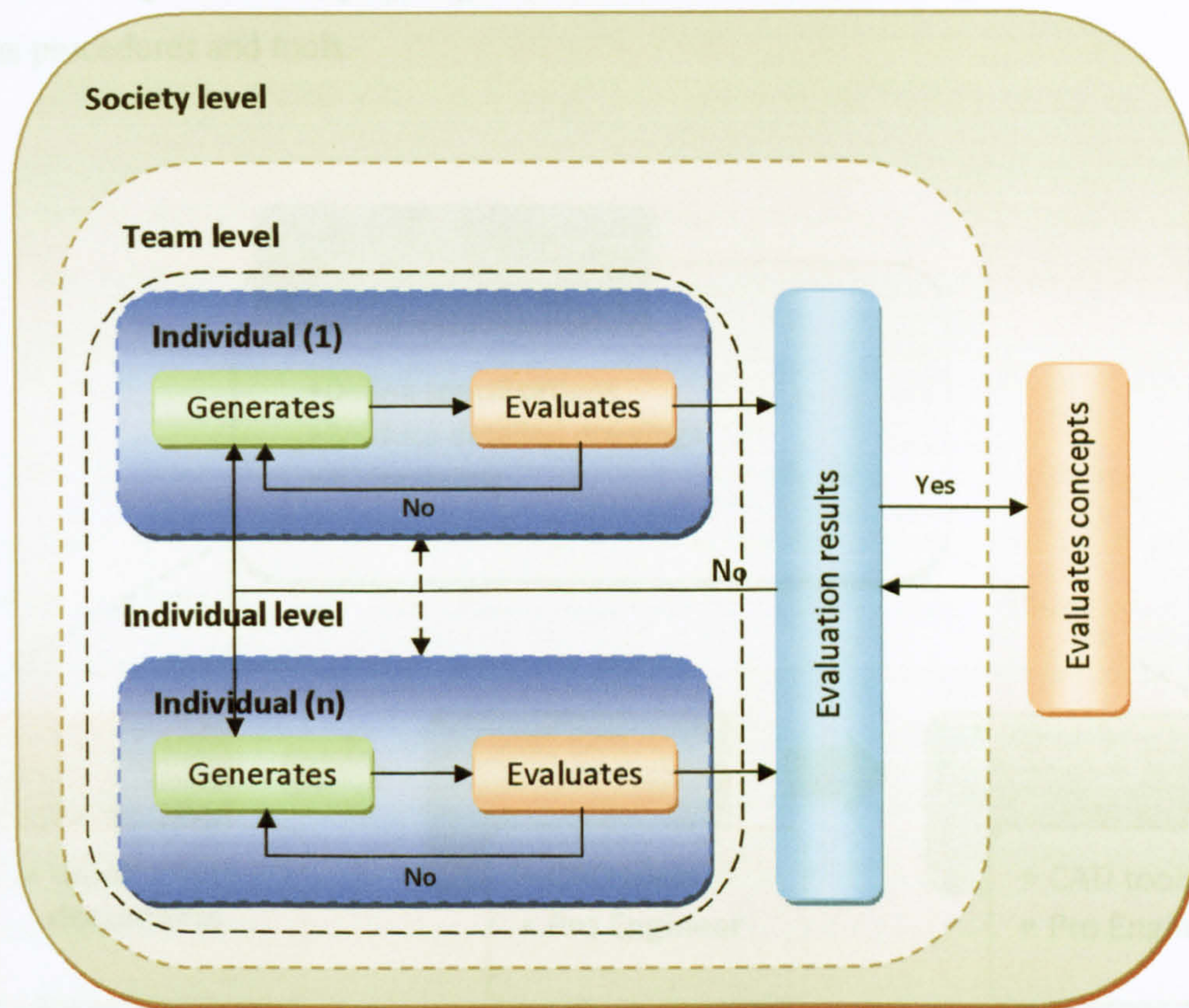


Figure 4.19 Proposed nested evaluation levels detailed

4.4.4.5 Detailed Design Module

Detailed design is the final stage in the design process before manufacturing. It requires great emphasis on detailing of each single component in the developed product. This necessitates the preparation of a comprehensive product specification which includes drawings, specifications and quality control measures. The preparation module incorporates several procedures to achieve a suitable satisfactory level of detailing and provides the team members with proper tools to accomplish this level. These procedures are: define specifications, produce working drawings, and 3D modelling. Several tools are integrated within the CDT system to accomplish these processes such as CAD tools and

Office tools. Figure 4.20 displays a generic view of the detailed design module showing the various procedures and tools.

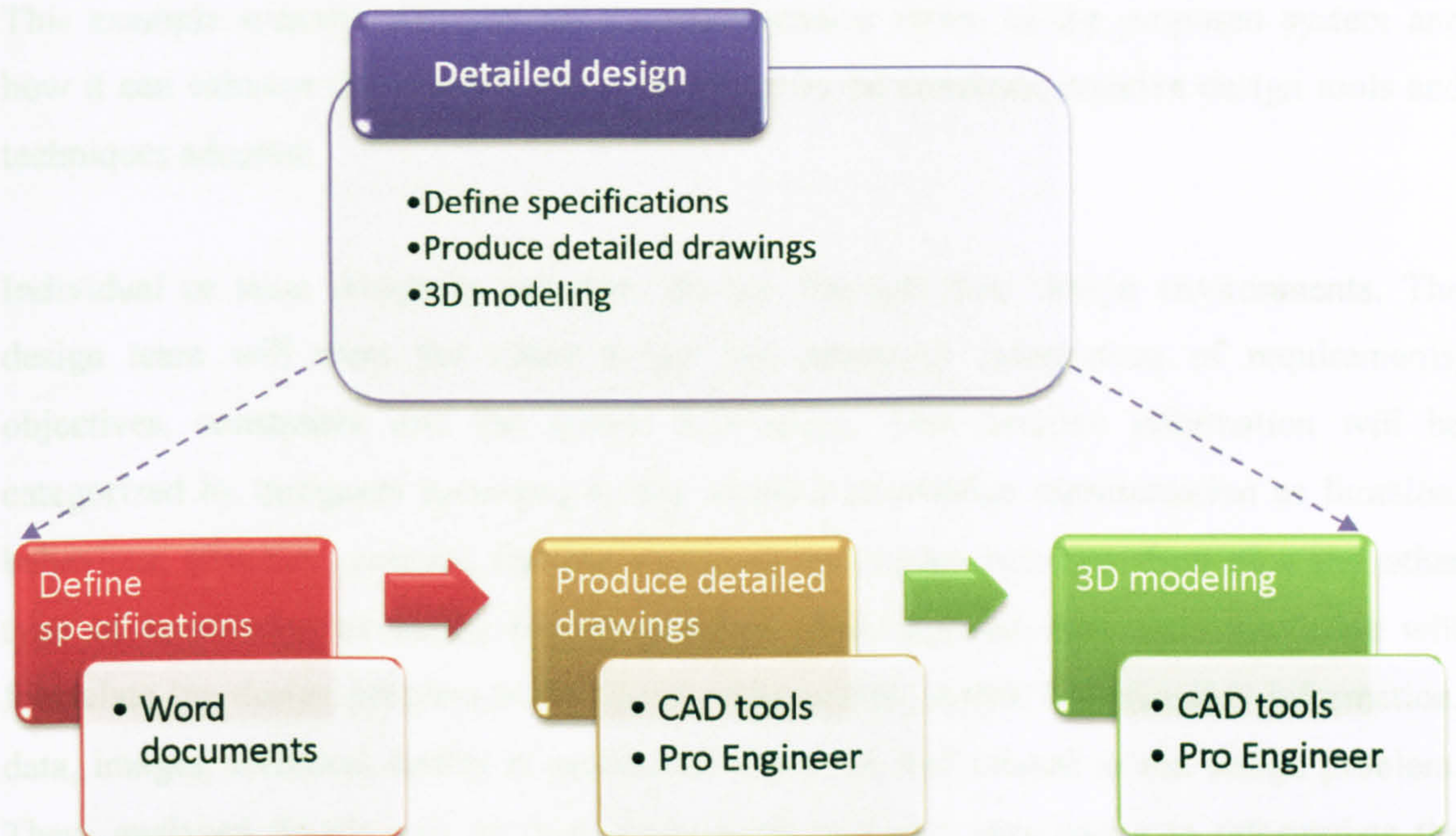


Figure 4.20 Procedures and tools in the detailed design module

4.4 Individual and Team Design Environments

The system provides each designer with his own design environment where he can explore the different parts of the system and work through the several modules. Each designer can conduct his design process according to his/her preference and use any of the incorporated tools. Furthermore, the system provides accessibility of the proposed design alternatives and knowledge produced by the individuals to the design team members. Therefore collaboration is achieved through ease of accessibility, sharing of knowledge, and using communication media like sending emails from within the CDT system. This guarantees speed in design team responses and communications.

4.5 Example Scenario of the Proposed System

This example scenario will provide a comprehensive vision of the proposed system and how it can enhance the creative design thinking by its concepts, creative design tools and techniques adopted.

Individual or team designers can start the job through their design environments. The design team will meet the client to get the necessary information of requirements, objectives, constraints and the related knowledge. This detailed information will be categorized by designers according to the adopted knowledge representation as function, behaviour, structure, context, and the relational knowledge between them plus any other type of knowledge necessary for the problem. The captured data and knowledge will formulate the design problem to be solved. Afterwards, search for necessary information, data, images, technical details is performed, analysed, and related to the design problem. These analysed details will be then synthesized in a new way trying to reformulate the design problem and come up with new variables to be added to the problem definition. This preparation process is flexible; for the design team can conduct any of the processes freely without any constraints. The result of this stage will structure the API database.

The design team already has developed a comprehensive idea of the requirements and actions to be taken. The concept generation stage can now be started by producing preliminary ideas through brainstorming sessions, concept mapping, and analogy tools by using any appropriate sketching media. These preliminary ideas need to be filtered and few will be selected to be processed by the combination and evolution tools. These tools can come up with totally new ideas that did not occur to the design team at the preliminary stage of concept generation. Hence more ideas can be added to the concepts' space after been evaluated by the design team and recognized as being creative. The chosen concepts are organized afterwards and displayed to select the most creative ones.

The selected concepts will be developed and enhanced by designers. Afterwards documentation of the positive points and negative points of each concept proposal will take place plus any supporting information for these concepts to be evaluated through the evaluation stage by the individual, team and society. The evaluation is based on multi dimensional criteria. The most creative concept will be processed to the final stage of detailed design to give the specifications, required working drawings and 3D modelling.

The flow of the design process is highly flexible and in the real situation will not follow exactly the outlined processes explained but will stop at some stages and go back to previous steps depending on the situation of the design problem and the emergence of any new ideas or concepts that need to be considered.

4.6 Summary

The proposed creative design concepts, methods, and tools have been presented in this chapter, showing the importance and relevance of the creative design thinking among designers for future design developments. The work comprises a generic system providing support for designers from the very early stages of design till the production of the detailed design drawings. The proposed approach has the following features:

- The capability of working individually and in collaboration depending on the situation of the design problem and design team.
- Holistic design platform that supports the different stages of the design process to the finest detail which combines state of the art creative tools to assist designers in producing more creative work.
- Up to date constructive databases which can be of great help for wide search and more creative conceptual designs.

- Creative and easy to handle constructive knowledge representation which can be achieved by the designers themselves.
- Human-centred design activities with the assistance of outstanding methods and tools.
- Flexible computational environment with the capability of integrating the work of designers using any conventional media the design team prefers.
- User-centred interface to achieve an easy interactive design environment for designers through simplicity and straightforward tools, views, and navigations.

CHAPTER FIVE

CREATIVE DESIGN THINKING (CDT) COMPUTATIONAL MODEL

5.1 Overview

The literature survey conducted and discussed in CHAPTER TWO showed an increase in the interest of design issues in general and design computation in specific. The tremendous increase in demand for more creative designs, the rapid growth in the customer market, and the rapid development of computing technologies; all these entire issues reveal the importance of design computing and how it can support designers to cope with these demands and changes in markets, and technologies.

This chapter highlights the importance of design computation in developing the proposed CDT system. The proposed framework presented in CHAPTER FOUR requires a well structured design knowledge representation to be used by the incorporated creative tools, processes, and databases. Suitable design representation guarantees easy retrieval, update, and identification of new design knowledge effectively. Once the design knowledge representation has been structured, the creative tools computational methods can be implemented using this structured representation of design knowledge. Subsequently, the integration of these tools and knowledge representations with the design process modules can produce creative solutions through the interaction between the design team members and these integrated elements of the proposed computational CDT system.

Section 5.3 describes the computational model of the CDT system starting with the design knowledge computation in section 5.3.1. The creative tools computation is detailed in section 5.3.2. Section 5.3.3 provides a comprehensive detailed explanation of the creative design modules and their relations with the tools and design knowledge. The user-centred

interface is presented in section 5.3.4. Furthermore, the design environment (situatedness in design) is discussed in section 5.3.5. Finally a summary is given in section 5.4.

5.2 *Introduction*

Competence in the future global market requires fast response to customer needs with great capabilities in designing and producing creative competitive products. Since this research adopted the view of creativity as a learnt skill, the development of tools and techniques to enhance creative thinking among designers is a must. Furthermore, new advancements of computer technologies such as the rapid changes in becoming more user friendly, large storing capabilities, speed in processing information, and World Wide Web require rapid adaptation from our side. Designers are one sector of the society that needs to adapt as fast as the speed of technological advances. Design computation developments can enhance designers' work tremendously through supporting design teams and enhancing their creative thinking, collaboration, and time management.

The main aim of using design computation in creative thinking is to force designers to escape the routine space of design to the non-routine space of new designs. The design space is changed and new solutions can be revealed by introducing new knowledge accompanied by flexibility in the design environment where design teams, tools and processes interact to create new solutions to the problem. Furthermore, designers should be able to update the design knowledge and add new structured knowledge during the design task according to the design problem situation such as goals, requirements, and constraints.

Furthermore, several activities addressed in the literature were found useful to be included in the CDT computational system. For example searching and browsing knowledge either in databases or other sources like the World Wide Web (www), collaborating among design team members, visualizing of design knowledge, exploring of new solutions by using various techniques like combination or analogical reasoning, reviewing of design

requirements and constraints through the design task, and many more activities detailed later in this chapter.

In the following sections the design computation of the proposed system is detailed to give a detailed view of the way the system has been computerized. Since the design process is a nonlinear process and is considered black box for most designers, computing it is not an easy procedure. Finding the proper representation of such an activity requires lots of comprehensive awareness of the nature of design and how designers think in addition to a wide knowledge in computing technology and its capabilities.

5.3 *Creative Design Tools computational model*

As described in CHAPTER FOUR the theme of the proposed CDT system has been based on the interaction between four vital elements for creative design thinking which are: design knowledge, design team, design processes, and creative tools. A common shared representation is required to achieve the most effective interaction between these elements. Design knowledge in the proposed CDT system symbolizes this shared representation. It is used by all other elements in the creative design environment. Design teams, tools, and processes all share the same design knowledge representation.

Design teams identify, update, and modify the design knowledge to define the design problem's boundaries, furthermore, they interact with the incorporated tools and processes through the displayed design representations. Therefore, it should be structured in a human-computer mode to be easily understood by the design team members and effectively used by the other elements.

Incorporated creative tools use the structured design knowledge representation either to create new concepts or to apply its embedded methods to explore more design solutions. Each tool has its own specific techniques that need to be developed in order to be

implemented computationally. Some of these tools methods have been addressed in the literature but required amendments and improvements to share the structured design knowledge of the proposed CDT system.

Design processes vary in their utilization or interaction with design knowledge representations. Preparation module for example supports design teams to identify new knowledge and modify existing ones. Concept generation module procedures activate the creative tools which in turn use the design knowledge to apply its methods and explore more options. Development, evaluation, and detailed design modules all share the same design knowledge but utilize it differently.

On the other hand, the user interface and the design environment of the proposed CDT system act as the common grounds which integrate the previously described elements of creative design thinking. These common grounds need to be designed to endorse the full use of the proposed CDT system capabilities. In the following sections a detailed computational description of the four creative design thinking elements and their common backgrounds are presented.

5.3.1 Design Knowledge Computation

Design knowledge in the developed CDT system constitutes a major element in the creative design thinking environment as discussed earlier. Computation of the CDT design knowledge has focused on the design knowledge representation from one side, and the design knowledge database management from the other side. Poor representations and management of design knowledge can hinder the objective of the design system to increase the production of creative ideas in remarkable time. Both sides are discussed in detail in the following sections.

5.3.1.1 *Design knowledge representation*

Representation of design knowledge is a major concern in implementing the (CDT) system for it can support or hinder the objective of the design system to increase their productivity in terms of creative ideas. The proposed design representation has been developed based on that proposed by Gero (1990) which includes function, behaviour, structure, and knowledge. In the developed CDT system each design alternative is divided into major components, each major component is divided into items with different identified features which distinguish it and specify its characteristics. For each component and item in the design alternative detailed functions, behaviours, and structures are identified in addition to the general ones of the alternative in this hierarchical structure. The incorporated creative tools are structured and implemented based on this hierarchical design representation. Features are structured to include structural, behavioural, and functional data. Relationships between different parts of the designed sample are identified using objects tree hierarchical structure and methods embedded within each object. The data identified in those representations are stored in the databases and can be retrieved and used by all the incorporated creative tools.

Design knowledge has been represented in the proposed CDT system using structured hierarchical tree. This hierarchical tree has been selected because it has many advantages over other knowledge representational schemes. These advantages are reflected in their easy connectivity to the databases to store and retrieve data, the flexibility and expandability of its structure where designers can add, hide, or show more detailing as required, and its adaptability to represent any hierarchical design knowledge for any product. An illustration of the concept alternative representation is shown in Figure 5.1.

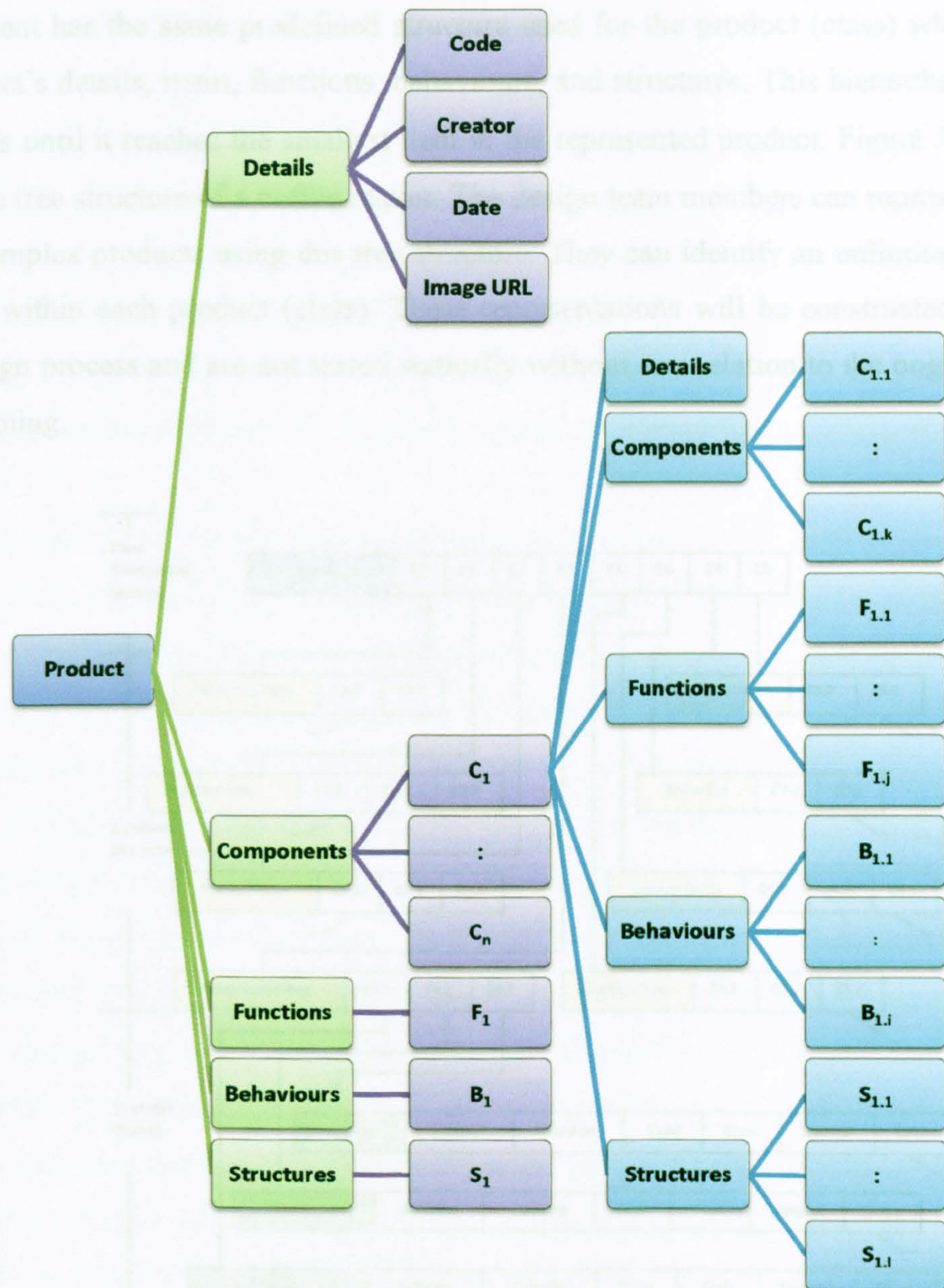


Figure 5.1 Illustration of concept hierarchical tree representation

Structuring of any product's tree to represent its knowledge starts by identifying the root node which represents the product as a class. This identified class has a predefined structure to represent its details, components, functions, behaviours, and structures. The second level in the tree is to identify the components of this product as objects in this class. Each

component has the same predefined structure used for the product (class) which displays the object's details, items, functions, behaviours, and structures. This hierarchical structure descends until it reaches the smallest item in the represented product. Figure 5.2 shows an example tree structure of a coffee maker. The design team members can represent even the most complex products using this tree structure. They can identify an unlimited number of objects within each product (class). These representations will be constructed along with the design process and are not stored statically without any relation to the ongoing process of designing.

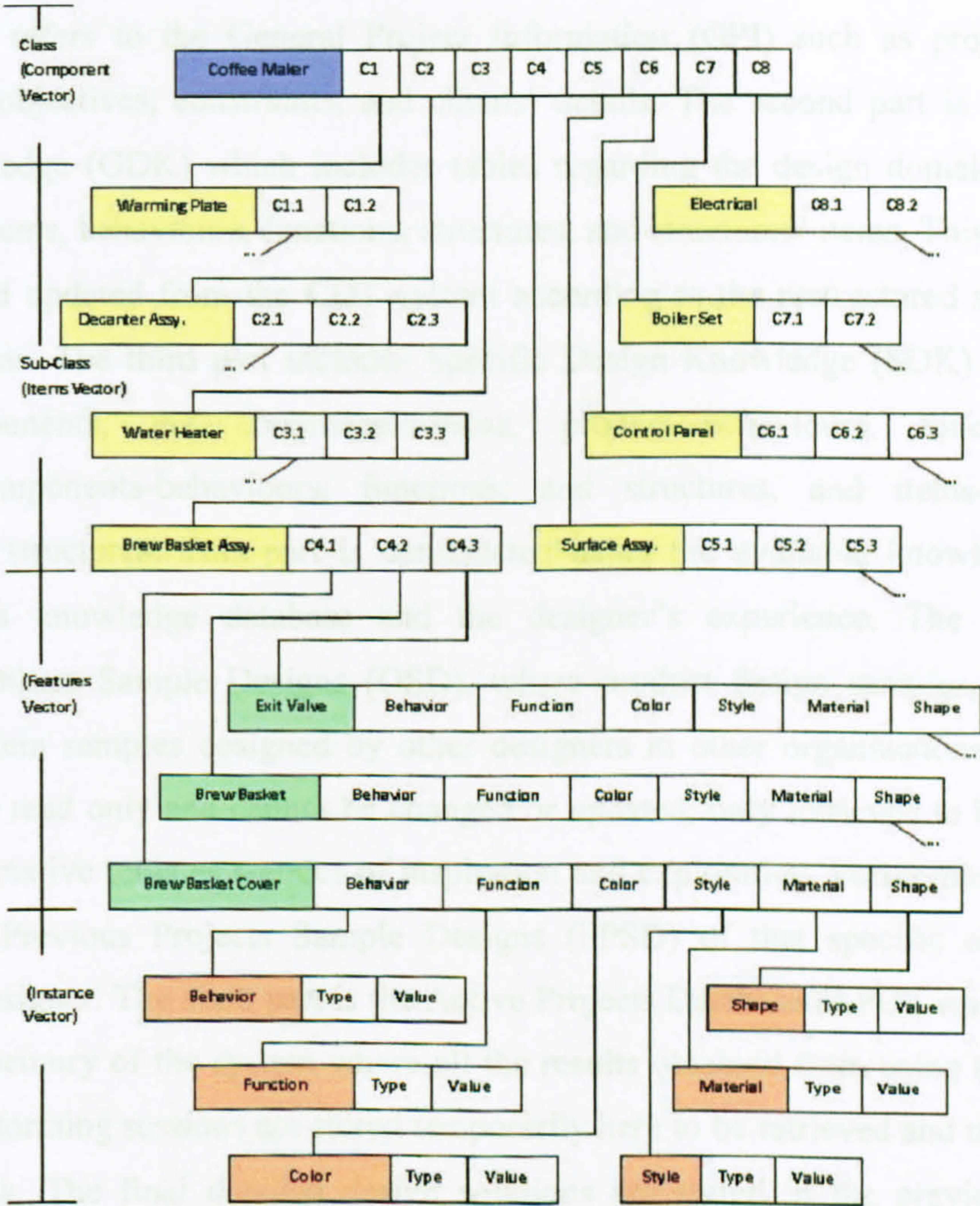


Figure 5.2 Example of a coffee maker tree structure

5.3.1.2 *Design knowledge database management*

Microsoft Structured Query Language (SQL) server 2005 was used to create the databases of the CDT system. The data related to products, major components, items, behaviours, functions, and structures are stored in relational tables. The developed CDT system contains structured design knowledge in its databases and allows performing of certain operations on that data such as retrieval, modification, insertion, and deletion. Design knowledge databases of the CDT system have been classified into six major parts.

The first part refers to the General Project Information (GPI) such as project details, requirements, objectives, constraints, and clients' details. The second part is the General Design Knowledge (GDK) which includes tables regarding the design domain, products, components, items, behaviours, functions, structures, and structures' items. This part can be maintained and updated from the CDT system according to the restructured situations of design problems. The third part includes Specific Design Knowledge (SDK) such as the products-components, the components-items, products-behaviours, functions, and structures, components-behaviours, functions, and structures, and items-behaviours, functions and structures. This part is constructed using the available knowledge in the general design knowledge database and the designer's experience. The fourth part incorporates Others Sample Designs (OSD), where product design samples, component samples and item samples designed by other designers in other organizations are stored. These data are read only and cannot be changed or updated, only retrieved to be copied to use with the creative tools as sources of inspiration and exploration. Furthermore, the fifth part contains Previous Projects Sample Designs (PPSD) of that specific organization, company or designer. The sixth part is the Active Projects Database (APD), which acts like the working memory of the system where all the results obtained from using the different tools or brainstorming sessions are stored temporarily here to be retrieved and used through the design task. The final detailed design solutions are stored in the previous projects database to be used in future design problems. The design knowledge of all the samples in

the last three parts of the databases is represented using the previously detailed hierarchical structured tree representation to provide consistency in the system.

The CDT system is designed with the perception of being universal to be used by any design domain or specialization. Any design organization can build its databases using the CDT windows, tables, and visual tools reflecting its specialization and way of thinking. Therefore, providing flexibility in knowledge structure is a major concern in the development of the CDT system. The flexibility of the proposed system is achieved by its adaptability to new design knowledge representation structures. In this research a general approach has been proposed which can be adapted to various design situations in the type of data stored in this main structure. This varies according to each design task and various specialties.

Data management in the developed CDT system has been divided into two major classes: general data management, and specific data management. General data management is concerned with general data identification that can fit any design problem. Designers can identify general data for the design problem under consideration to be used later to identify the specific data for the same problem. This total management of data allows the system to be used for various design problems' types since any relative data can be identified easily and immediately to suit that specific situation by the designers themselves without any amendments in the system's structure.

The identified general data is stored in the databases through the user interface of the CDT system. Designers can view the existing data in grid views and by a click of a button can add, update, or delete data as required. Data identified in this class includes design domains, products, components, items, and features (functions, behaviours, and structures). It is identified as a stand alone data without any relation or connection to any other type of data or other objects. Figure 5.3 illustrates a sample window of the general data management.

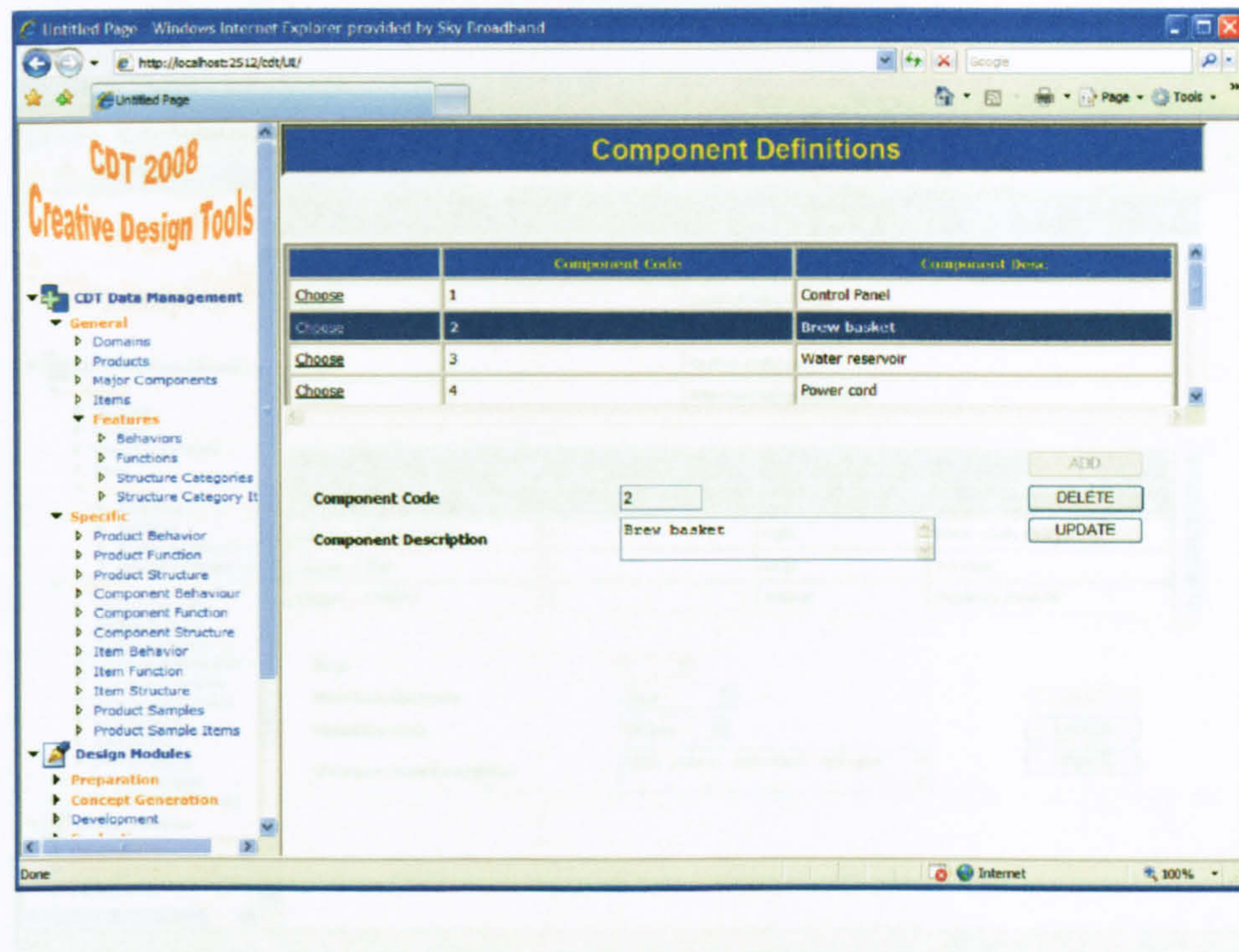


Figure 5.3 Component definitions window (general data management)

Figure 5.4 Product structure definitions window (specific data management)

The specific data management class utilizes the previously identified general data to identify new specific data related to the design problem situation. It relates the identified features (functions, behaviours, and structures) with the identified products, components, and items. This data management class provides the base for the design knowledge representation structured at later stages in the developed CDT system. Figure 5.4 illustrates a sample window of the specific data management.

A major concern in developing this data management was to facilitate the addition and modification of data in no time through a user friendly interface where designers can view the existing and the modified data at all times. Therefore, a grid view has been integrated in the user interface where the existing data is displayed as records. Each record can be selected to be modified or deleted. New records can be added as well, displayed immediately in the grid view and stored in the database at the same time. This grid view is used to display all data types mentioned earlier.

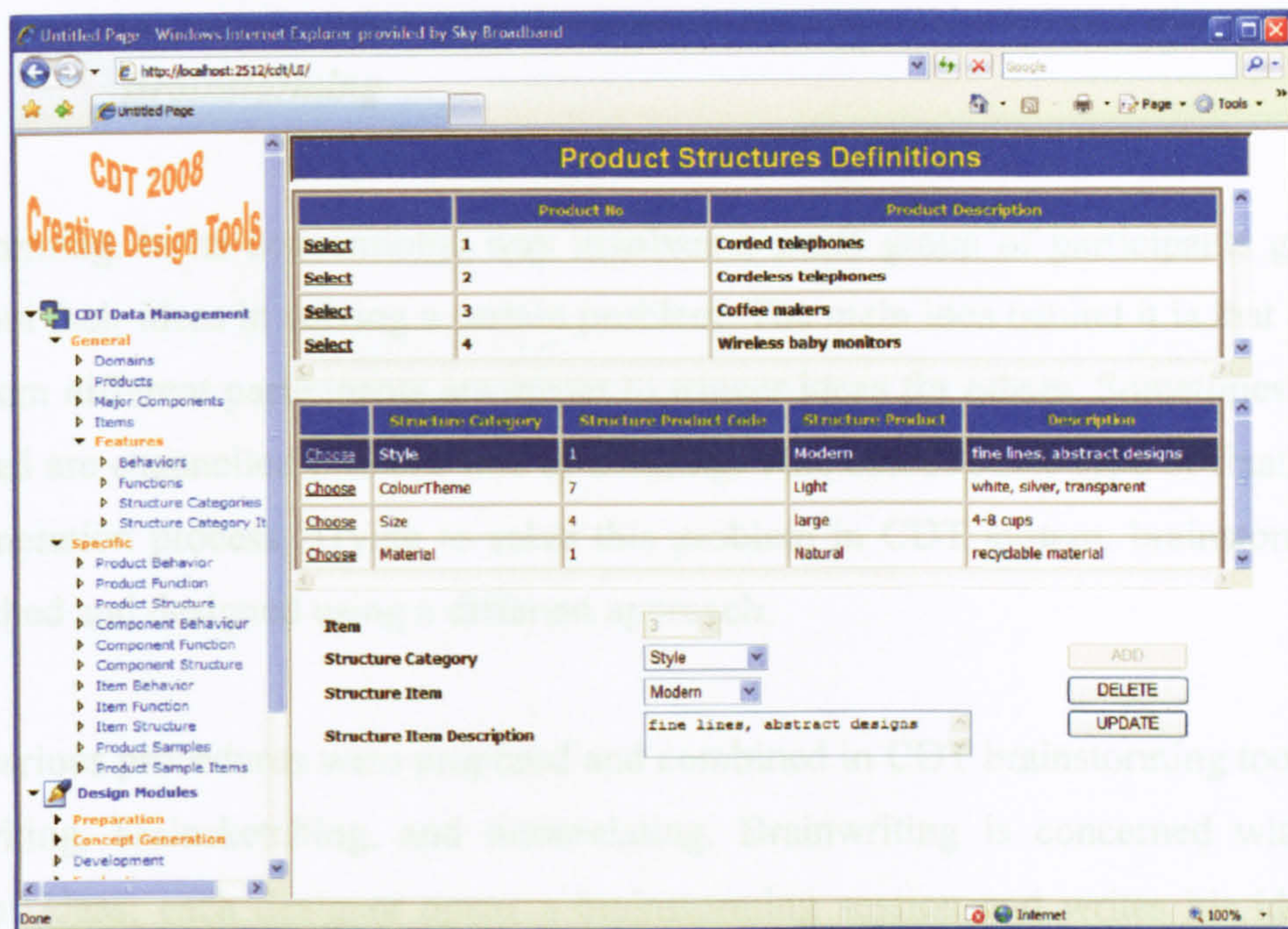


Figure 5.4 Product structures definitions window (specific data management)

5.3.2 Creative Tools Computation

Various creative tools have been developed and incorporated in the developed CDT system. These creative tools involve divergent thinking procedures to create and explore a wide net of design concepts for the design team. They encompass idea generation focused activities and exploratory techniques such as brainstorming, conceptual mapping, analogical reasoning, combination and evolutionary methods. Its main aim is to facilitate the generation of new ideas and to widen the search and exploration spaces for designers. Computational methods have been developed for each incorporated tool in the CDT system to facilitate the implementation of its activities by the design team. The following sections discuss the developed computational methods for each incorporated creative tool in the developed CDT system.

5.3.2.1 *Brainstorming*

Brainstorming, in its conventional way involves a small group of participants gather and talk about their ideas in solving a certain problem. The main idea behind it is that generated ideas from different participants are meant to trigger ideas for others. Sometimes the ideas generated are channelled into one line of thinking. This causes some type of fixation in the idea generation process. Trying to solve this problem in CDT system, brainstorming was approached and designed using a different approach.

Three various procedures were proposed and combined in CDT brainstorming tool namely: brainwriting, brainsketching, and brainrelating. Brainwriting is concerned with written forms of ideas; each designer opens a brainstorming session and writes his ideas down using text tools. Furthermore, the designer draws or sketches the ideas using conventional manual media or incorporated CAD tools which is referred to as brainsketching. Brainrelating is about defining concepts and clustering certain ideas together and relating them. Hexagon diagrams in Axon2008 commercial tool were used to build the brainrelating diagrams in CDT brainstorming. The results of these three procedures are saved in the active project database as brainstorming ideas. Each idea has a unique number to identify it and the designer who created it with the date it was created. The details of these ideas can be retrieved and reviewed by other designers after the session has ended. In this way each designer at the beginning generates ideas without any influence from others; at later stages of the idea generation process ideas generated by others are viewed and evaluated to select the most suitable ones for further development.

Some extra functions are added to the brainstorming tool such as opening the calculator application, searching the World Wide Web, and navigating to concept mapping tool. The generated concepts are not stored in the proposed design representation format; therefore, the supplementary creative tools could not be applied on these generated concepts.

Structuring brainstorming concepts into the proper design representation is achieved through the concept mapping tool. Figure 5.5 displays the general layout of the brainstorming tool window from the developed CDT system.

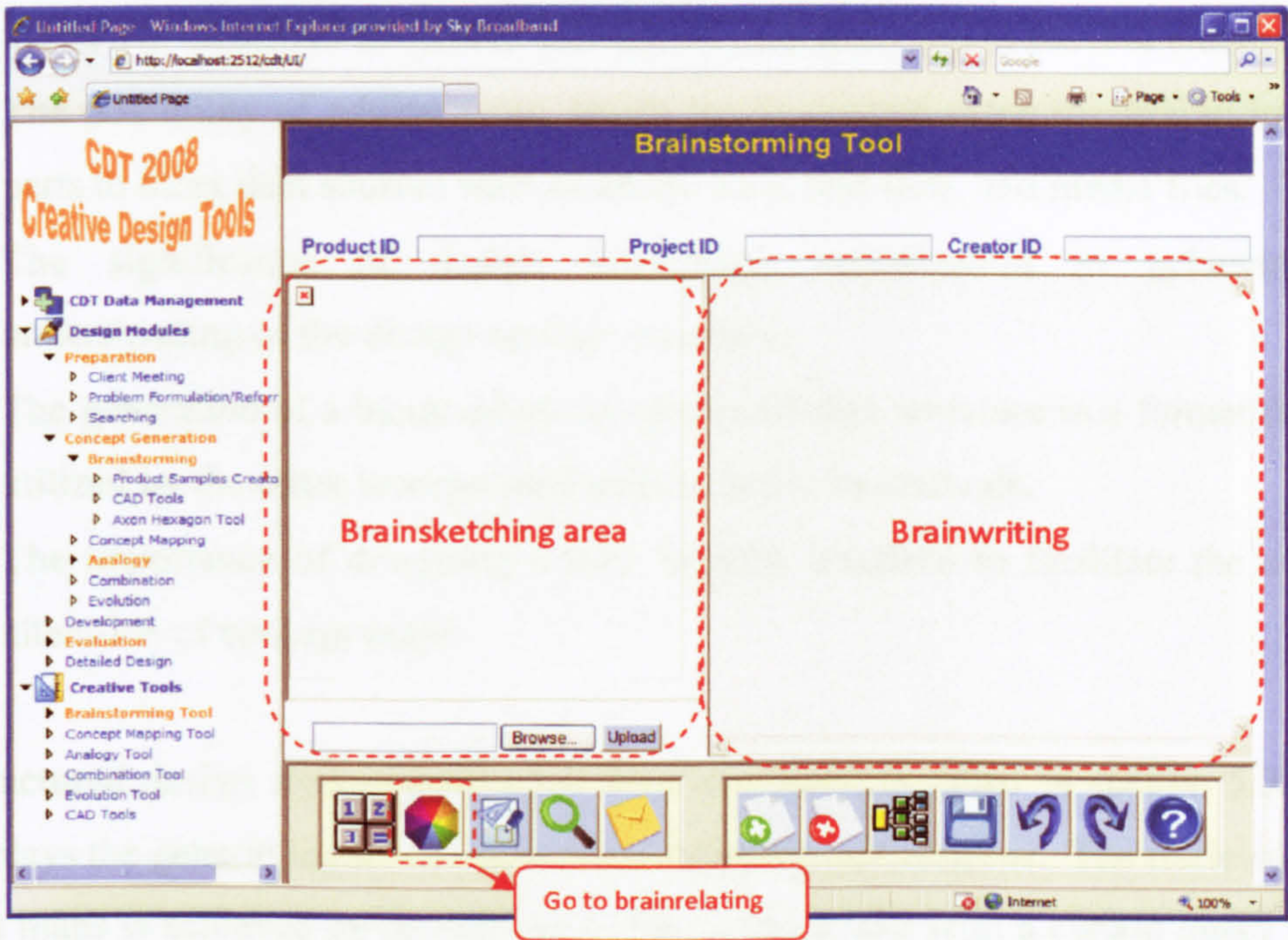


Figure 5.5 Brainstorming tool layout window

5.3.2.2 *Concept Mapping*

The concept mapping tool incorporated in the developed CDT system comprises several activities. These activities involve externalizing of design structured knowledge to create new concept maps that represent the design knowledge of the newly generated concepts, retrieving and modifying existing concept maps, visualizing the generated design representational maps, and store the created concept maps in the databases. This tool has been developed taking into consideration several important issues:

- The flexibility of design knowledge conceptual map trees to include various numbers of components since each product has its own structure and contains a different number of components.
- The importance of connecting the concept mapping tool with the databases to store the newly identified structured conceptual map trees and to retrieve existing ones.
- The possibility of adding more details to the created maps by linking its different parts to other data sources such as image files, text files, and media files.
- The significance of design knowledge visualization in achieving better understanding of the design concept structure.
- The generation of a hierarchical design knowledge structure in a format that can be utilized by the other incorporated tools to apply its methods.
- The importance of designing a user friendly interface to facilitate the creation or alteration of concept maps.

The structured design representation has been discussed in detail in section 5.3.1. Figure 5.6 displays the general layout of the concept mapping tool window. The retrieval of stored concept maps is achieved by connecting to the database and with a certain query statement the data is retrieved and presented in the conceptual tree view. The designer decides on the type of that query by first specifying if the concept's map relates to a product, a component, or an item, then selects the object from the chosen category displayed to him to retrieve its concept map.

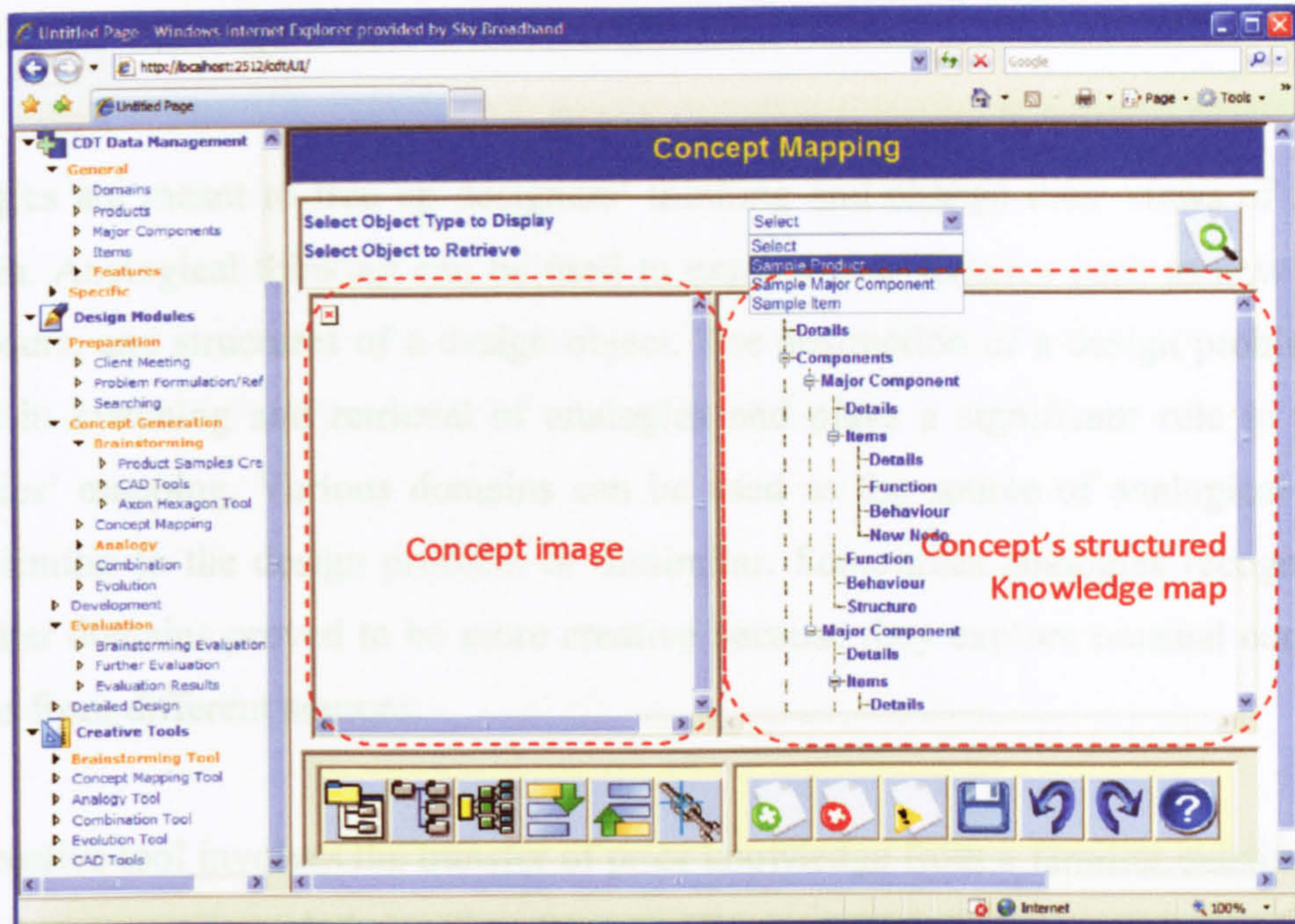


Figure 5.6 Concept mapping tool layout window

Besides the retrieval of existing concept maps, new concept maps can be built by using the provided buttons to add tree nodes. Each added node has five other children nodes connected to it representing the design object's details, components, behaviours, functions, and structures related to that specific object. This structure as mentioned earlier can be repeated for all components and items. This ability of constructing structured new concept maps provides flexibility for designers to add new knowledge to the CDT system but within the boundaries of the adopted design representation. Tree nodes can be linked to various data forms such as images, documents, and media.

The created concept maps can be expanded partly or as a whole to ease managing of its various parts. A window beside the tree structure displays the image of the selected object to support visual perception of designers. The functionality of all graphical tools used in the concept map tool interface is discussed in CHAPTER SIX.

5.3.2.3 *Analogy*

Analogies are meant to free up designers' thinking and change their views of the design problem. Analogical thinking can be used to explore new features such as new functions, behaviours, and structures of a design object. The abstraction of a design problem is very crucial in matching and retrieval of analogies and plays a significant role in successful analogies' mapping. Various domains can be used as the source of analogical reasoning either similar to the design problem or dissimilar. Sometimes analogies recognized from dissimilar domains proved to be more creative because they explore unusual combinations of ideas from different sources.

This creative tool involves the transfer of prior knowledge from a familiar existing situation (source) to a new revealed situation (target). This requires a source space, a target space, and a modified space. The computation of this tool can be expressed as Gero (2000) suggested as follows:

$$S_{\text{target}} = \tau_a (S_{\text{source}}) \quad (1)$$

where τ_a = analogical operation

This tool has a certain procedure which can be summarized in two main steps namely: matching and retrieval, mapping and transformation. In most design cases matching and mapping is based on the structure of artefacts, few cases were found to be based on the behaviour or function of these artefacts. The computations of these two steps were discussed by Gero and Kazakov (1999) as follows:

- Matching and retrieval: in this step the artefact with the highest similarity is retrieved for further processing.

$$\text{SIM} (D_T, D_S (i)) = \max_k \text{SIM} (D_T, D_S (k)) \quad (2)$$

where $SIM (*,*)$ is a real function which measures the degree of similarity between its parameter spaces, $D_S(i)$ is the i -th source design state space, and D_T is the target design state space.

- Mapping and transformation: in this step mapping adds some design variables from the i -th source design state space to the target design state space and then transforms the result of this operation into a modified design space D^m .

$$D^m = \tau (D_T \cup M (D_S(i))) \quad (3)$$

where M is a mapping operation, and τ is a transformation operator.

Knowledge from the target state space is passed to the modified space to be analyzed and checked if any of its existing relationships are not supported by its current knowledge. If not, some additional parts of knowledge from the source state space are identified and added to the modified design state space. This can go on until certain analogies are mapped and found creative by the design team.

In the developed CDT system the functions that measure similarity for matching and retrieval of analogies are based on one or more of the identified design features. It is built on finding similarities between functions, behaviours, and/or structures of design objects between the source design state space and the target design state space. Certain values for these features are identified by the designers to start the matching and retrieval according to them. Furthermore, the source design state space is chosen by the designer by deciding on the categories to search in such as sample products, sample components, sample items, any other source like images for example, or all of the mentioned categories. Searching all of the provided categories can be more useful in analogies but can cause some overloads in memory.

The originality in the analogical tool developed and incorporated in the CDT system is its capability to match and retrieve design objects based on multi parameters not only one

parameter as described in previous work in the literature. For example objects can be matched and retrieved using behaviour, function, and structure parameters not only one of them. This theme constrains the search results and focuses the solution in specific directions. Later on these constraints can be minimized and fewer numbers of parameters can be used to retrieve data such as function and behaviour, function and structure, behaviour and structure, function alone, behaviour alone, or structure alone. Therefore the CDT system provides flexibility in maximizing and minimizing the analogical parameters or constraints according to certain particular situations. The computation of the developed CDT analogical matching and retrieval activity is modelled as follows:

$$\text{SIM} (D_T (Ft), D_S (Ft)) \quad (4)$$

where $\text{SIM} (*, *)$ is a real function that measures similarity between the two design spaces, D_T = the target design state space, D_S = the source design state space, Ft = the features of the design object namely: function, behaviour, and structure. The matching and retrieval can be conducted using one, two, or the whole three features as modelled in the following:

$$\text{SIM} (Fn_T, Fn_S (i)) = \max_k \text{SIM} (Fn_T, Fn_S (k)) \quad (5)$$

$$\text{SIM} (B_T, B_S (i)) = \max_k \text{SIM} (B_T, B_S (k)) \quad (6)$$

$$\text{SIM} (S_T, S_S (i)) = \max_k \text{SIM} (S_T, S_S (k)) \quad (7)$$

$$\text{SIM} [(Fn_T, Fn_S (i)) \cup (B_T, B_S (i))] = \max_k \text{SIM} [(Fn_T, Fn_S (k)) \cup (B_T, B_S (k))] \quad (8)$$

$$\text{SIM} [(Fn_T, Fn_S (i)) \cup (S_T, S_S (i))] = \max_k \text{SIM} [(Fn_T, Fn_S (k)) \cup (S_T, S_S (k))] \quad (9)$$

$$\text{SIM} [(B_T, B_S (i)) \cup (S_T, S_S (i))] = \max_k \text{SIM} [(B_T, B_S (k)) \cup (S_T, S_S (k))] \quad (10)$$

$$\text{SIM} [(F_{n_T}, F_{n_S}(i)) \cup (B_T, B_S(i)) \cup (S_T, S_S(i))] = \max_k \text{SIM} [(F_{n_T}, F_{n_S}(k)) \cup (B_T, B_S(k)) \cup (S_T, S_S(k))] \quad (11)$$

where F_{n_T} is the target function space, $F_{n_S}(i)$ is the i -th source function space, B_T is the target behaviour space, $B_S(i)$ is the i -th source behaviour space, S_T is the target structure space, and $S_S(i)$ is the i -th source structure space.

Mapping recommences using the chosen concepts. It can be structural-based, functional-based and/or behavioural based. It is conducted at the level of the features values where these values are either combined or substituted. The proposed mapping procedures are modelled as follows:

$$D^m = F_n^m \cup B^m \cup S^m \quad (12)$$

$$F_n^m = \tau (F_{n_T} \cup M (F_{n_S}(i))) \quad (13)$$

$$B^m = \tau (B_T \cup M (B_S(i))) \quad (14)$$

$$S^m = \tau (S_T \cup M (S_S(i))) \quad (15)$$

where D^m is the modified design space, F_n^m is the modified function space, B^m is the modified behaviour space, S^m is the modified structure space, τ = a transformation operator, and M is a mapping method.

5.3.2.4 *Combination*

The combination tool is built on combining two or more different samples, components, or items to come up with a new one, or to combine two or more different features' values to create a new one. When computerized; this tool can provide designers with more

combination alternatives which might trigger a hidden creative idea. The computation scheme is described in the following:

$$P_{\text{new}} = P_1 \cup P_2 \cup \dots P_n \quad (16)$$

$$P_n = [C_1, C_2 \dots C_i] \quad (17)$$

$$C_i = [C_{i1}, C_{i2} \dots C_{ij}] \quad (18)$$

$$C_{ij} (F) = [F_{ij1}, F_{ij2} \dots F_{ijk}] \quad (19)$$

$$F_{ijk} = [t, v] \quad (20)$$

where n is the number of products to be combined, i is the number of components to be combined, j is the number of sub-components to be combined, k is the number of features to be combined, t is the type of feature to be combined, and v is the value of feature to be combined.

This technique can be achieved on a structural, functional, and behavioural level. Four methods of combination are developed in the CDT system: systematic combination, tree random combination, vertices random combination, and total random combination. The four methods are based on the tree design representation described earlier. The four mentioned combinational methods are illustrated in detail in the following:

- *Systematic Combination*

In systematic combination the trees are chosen in order and the combination is achieved systematically between the different trees and vertices one by one.

$$\begin{matrix} n & k \\ \{ \{ u_{ij} \} \} \\ j=1 & i=1 \end{matrix} \quad (21)$$

where n is the number of vertices in each tree, and k is the number of trees.

- *Tree Random Combination (choosing the trees randomly)*

In the tree random combination the trees are chosen randomly but the combination between those trees' vertices are conducted systematically.

$$\begin{matrix} n & k \\ \{ \{ V_{g(i)j} \} \} \\ j=1 & i=1 \end{matrix} \quad (22)$$

where g is a permutation on $\{1, 2, 3, \dots, k\}$, n is the number of vertices in each tree, k is the number of trees.

- *Vertices Random Combination (choosing the vertices randomly)*

In this method the vertices are chosen randomly but the trees are chosen systematically.

$$\begin{matrix} n & k \\ \{ \{ V_{if(j)} \} \\ j=1 & i=1 \end{matrix} \quad (23)$$

where f is a permutation on $\{1, 2, 3, \dots, n\}$, n is the number of vertices in each tree, and k is the number of trees.

- *Total Random Combination (choosing the trees and vertices randomly)*

In this method of combination the trees and the vertices are chosen randomly.

$$\begin{matrix} n & k \\ \{ \{ V_{g(i)f(j)} \} \} \\ j=1 & i=1 \end{matrix} \quad (24)$$

where g is a permutation on $\{1, 2, 3, \dots, k\}$, f is a permutation on $\{1, 2, 3, \dots, n\}$, n is the number of vertices in each tree, and k is the number of trees.

The described methods have been incorporated in the CDT system and the designers are given the choice to select the combination method according to their preference.

Furthermore these methods can be applied to pre-selected design alternatives by the designers, or it could be applied on the design samples stored in the databases and the results are displayed to evaluate and select the appropriate ones for further development.

5.3.2.5 *Evolution*

Evolution has been used as an optimiser in most cases, and as an explorer in recent cases concerning conceptual designs. The second option is adopted in the CDT system. This tool involves two main processes namely: cross over and mutation. The computation of these two major processes in the developed evolution tool is modelled as follows:

- Cross over is the crossing between parts of the tree structure from two or more parents. It can be modelled as:

$$P_{\text{new1}} = [P_{\text{parent1}} - P_{t_{\text{parent1}}}] \cup P_{t_{\text{parent2}}} \quad (25)$$

$$P_{\text{new2}} = [P_{\text{parent2}} - P_{t_{\text{parent2}}}] \cup P_{t_{\text{parent1}}} \quad (26)$$

where P_t is part of the design object tree structure, and P is the whole design object tree structure.

- Transformation (Mutation) is the alteration of one or more features variables by an external process. It can be modelled as Gero(2000) described:

$$P_{\text{new}} = \Phi_m (P_{\text{existing}}) \quad (27)$$

where Φ_m is a transformation operator such as re-sizing, re-colouring, re-shaping, changing materials, and many other transformational operations.

Two main issues which are considered crucial in such a creative tool are: a good design knowledge representation which enables the uncovering of a wide range of alternatives, and the removing or relaxing of constraints which can produce more creative alternatives. By using the tree design knowledge representations described earlier; this tool can be applied to any design knowledge available in any design process. In the developed CDT system a collaborative evolutionary tool is incorporated which requires more human interaction with the process to replace the fitness functions. The designers are also provided with the flexibility of choosing the evolutionary process to be conducted and the design objects which are used as the parents in the evolutionary tool. The tool can be started, paused, and stopped during the evolutionary iterations. Moreover the evaluation of the suitable generations is achieved by the designers. The main aim of using the evolutionary tool in the developed CDT system is to explore an extensive space of various conceptual solutions; as more time is spent in exploring the tool, more alternatives are created, and the exploration space is enlarged.

5.3.3 Design Modules Computation

The incorporated five design modules explained in CHAPTER FOUR are displayed in the following sections from a computational viewpoint. Each design module has its own activities and procedures to be applied and support the design process. Further detailing of the integrated activities of each design module is discussed with emphasis on the computational aspect of their implementation.

5.3.3.1 *Preparation Module*

The incorporated preparation module plays an important role in the creative design process discussed in CHAPTER FOUR. It involves two various ways of thinking; divergent and convergent. Divergent thinking is to create a broad space to catch all possible aspects of the design problem and all possible perspectives to its solution. Convergent thinking reduces the broad possibilities to a single controllable problem definition.

Divergent thinking in this design module has been supported by several activities. Each activity has been implemented to be displayed in a single window to achieve better interaction and visualization for the design team members. These activities include general data management, specific data management, and search. The general data management activity has several window interfaces where the designer can manage the general data in the databases. Each table in this specific database has been displayed in a data grid view which is a tabular form web control. The displayed data can be selected to be updated or deleted and the result is displayed immediately in the grid view control. This has been applied to all the windows in the general and the specific data management activities.

Search activity is approached differently; the search interface is designed to apply its methods using the designer's input. Designers can search the databases incorporated for similar products in the same domain, or search for any other samples in any other domain using specific search parameters to retrieve data. The search parameters used are the function, behaviour, and structure features identified by the designers themselves. The designer enters the value of one or more of these parameters and the system retrieves the related data and displays it in tabular form to visualize comprehensively. These features are displayed in drop-down list controls to select from. These drop-down lists are updated each time the databases are modified. The designer selects any interesting data and stores it in the active project design samples to be referred to if needed. Furthermore, the option of searching the World Wide Web (www) is available from the CDT environment. The selected interesting data are stored in the active project design samples in a special table for www search results. The search results can be useful in providing new visions or views of the design problem to help in formulating the problem or even generating solutions.

Convergent thinking is supported by other activities that deal with the identified abstract knowledge in the divergent thinking stage. The first activity is face to face interviews with clients which were referred to as client meetings in the CDT system. In client meetings various knowledge types are collected regarding the design requirements, likes, dislikes,

constraints such as time limits or budgets. This collected information is stored in the database to help designers in the problem formulation at later stages. During the interview designers can use the CDT client meeting window to enter the details immediately in the related database. Figure 5.7 shows a snap shot of the client meeting window.

CDT 2008 Creative Design Tools

Client's Meeting

Client's Details

Client's Name	Sunbeam/Mr coffee	Client's Address	P.O. Box 948379
Client's ID	MC004		Martland, FL 32795-0000
Client's Mobile	07866963247	Client's Telephone	18006726444

Project's Details

Project's Code	CM001	Project's Name	Mr coffee designs
Project's Domain	Kitchen Appliances	Project's Product	Coffee makers

Project's Objectives

Modern style
Includes new behaviours for the various parts
Energy saving
Create affordable solution

Project's Constraints

Use of existing manufacturing processes without new production lines
Limited budget to create a new product with high standards

Figure 5.7 Client meeting sample window

Problem formulation/reformulation activity is conducted last in the convergent thinking stage. After the design team has identified abstract knowledge regarding the design problem and started to focus its attention to identify the problem space through client meeting, the problem formulation can be detailed to decide on the goals and boundaries of the design problem using the identified data. A problem definition window has been developed in the CDT system to facilitate this activity to take place and to store the problem's defined goals, requirements, and constraints in the relative database. Figure 5.8 illustrates a problem formulation sample window.

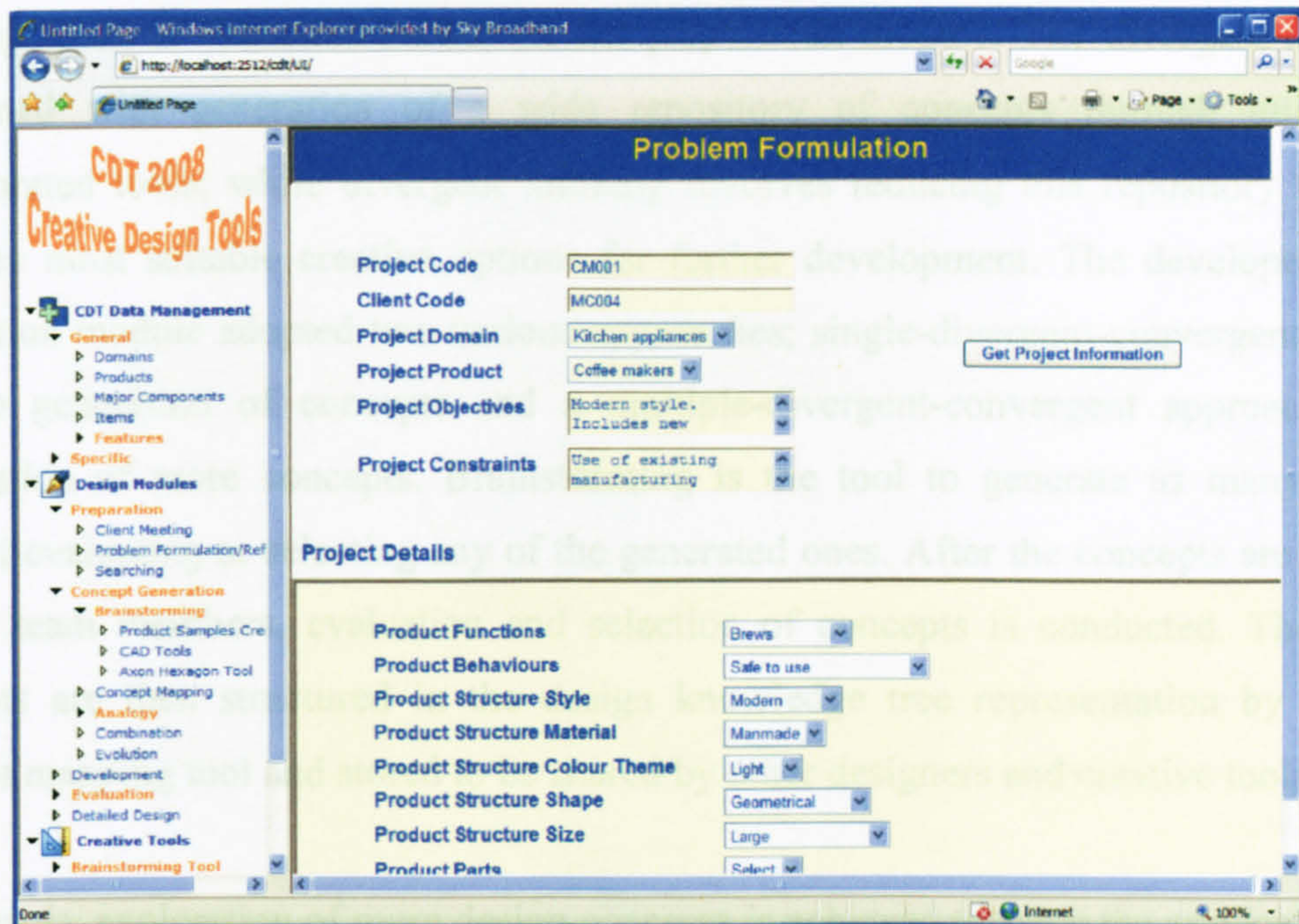


Figure 5.8 Problem formulation sample window

This preparation module incorporates several activities which have been recognized to be crucial for the creative process. These module activities are vital for the problem identification which is one of the important stages of this creative process. Therefore, a great emphasis has been given to the preparation module in the CDT system which uses several divergent and convergent thinking actions to identify the boundaries of the design problem under consideration. An issue that is worth mentioning is the ability to refer to this module's activities as much as needed through the various design process. If the designer recognized the need to identify a new knowledge, it is possible to do that during any active project and it will be reflected to all users. This shows the flexibility of the CDT system and its ease of navigation.

5.3.3.2 Concept Generation Module

Concept generation module focuses on three activities; generation, structuring, and exploration of design concepts. It involves two ways of thinking; divergent and convergent

thinking types as discussed earlier for the preparation module. The divergent thinking is concerned with generation of a wide repository of concepts through utilizing the incorporated tools; while divergent thinking involves reducing this repository to include only the most suitable creative options for further development. The developed concept generation module adopted two various approaches; single-divergent-convergent approach for the generation of concepts and a multiple-divergent-convergent approach for the exploration of more concepts. Brainstorming is the tool to generate as many concepts without evaluating or selecting any of the generated ones. After the concepts are shared by all the team members, evaluation and selection of concepts is conducted. The selected concepts are then structured in the design knowledge tree representation by using the concept mapping tool and stored to be shared by other designers and creative tools.

Afterwards, exploration of more design concepts is achieved through the application of the incorporated creative tools. A multiple divergent-convergent approach has been applied in applying these tools. This means that while using each creative tool to explore options, the methods of each tool are implemented, and then the results are displayed and screened to select the appropriate options for further application either using the same tool or some other tool. The selected concepts are then stored for further evaluation and development. Therefore all the stored exploration concepts are evaluated as creative by some means or have potential to be creative with some extra development. Figure 5.9 displays the multiple divergent-convergent approach of the concept generation module, and figure 5.10 illustrates the computational activities of the same module.

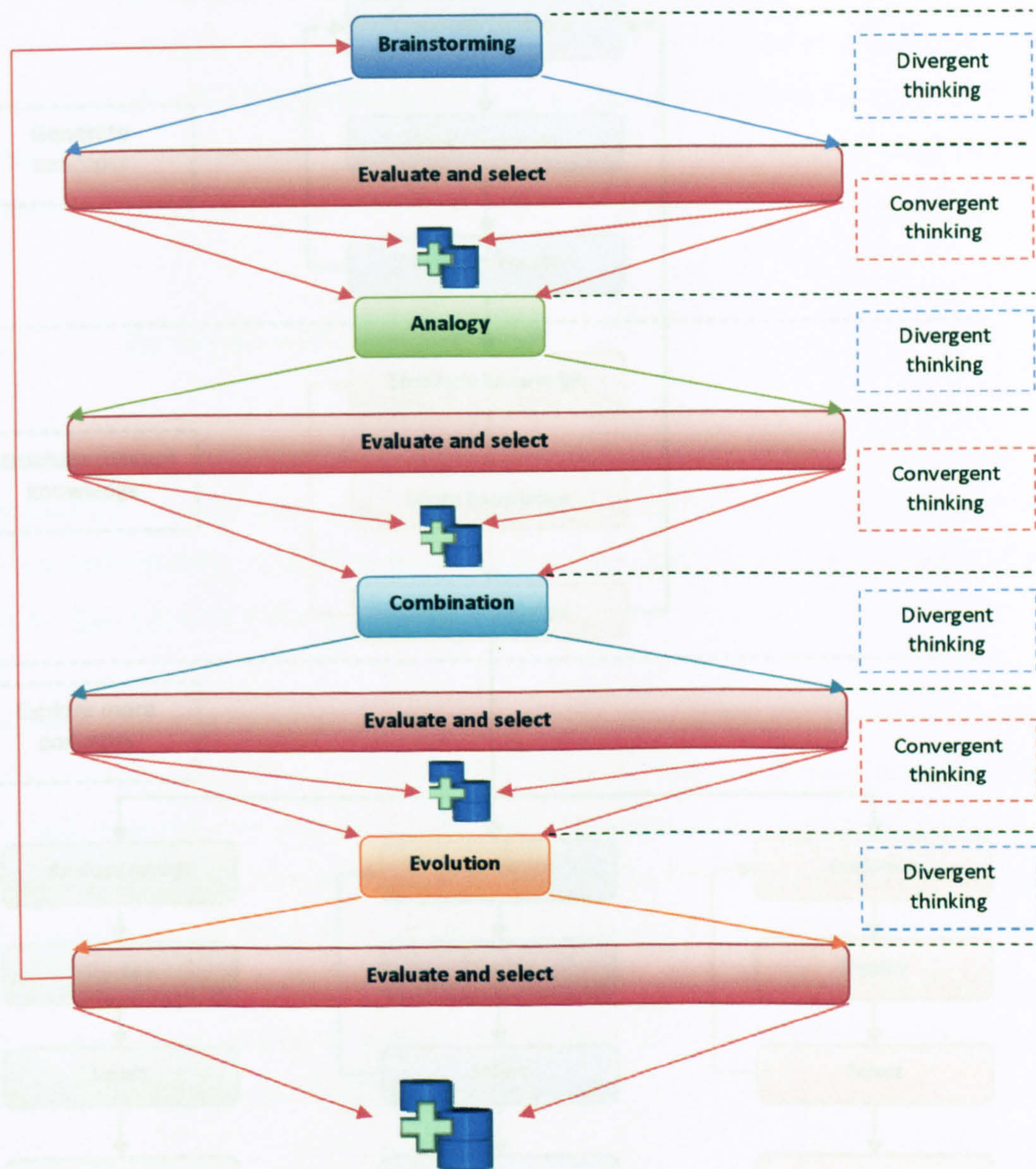


Figure 5.9 Divergent-convergent approach of the concept generation module

Figure 5.10 Computational activities of the concept generation module

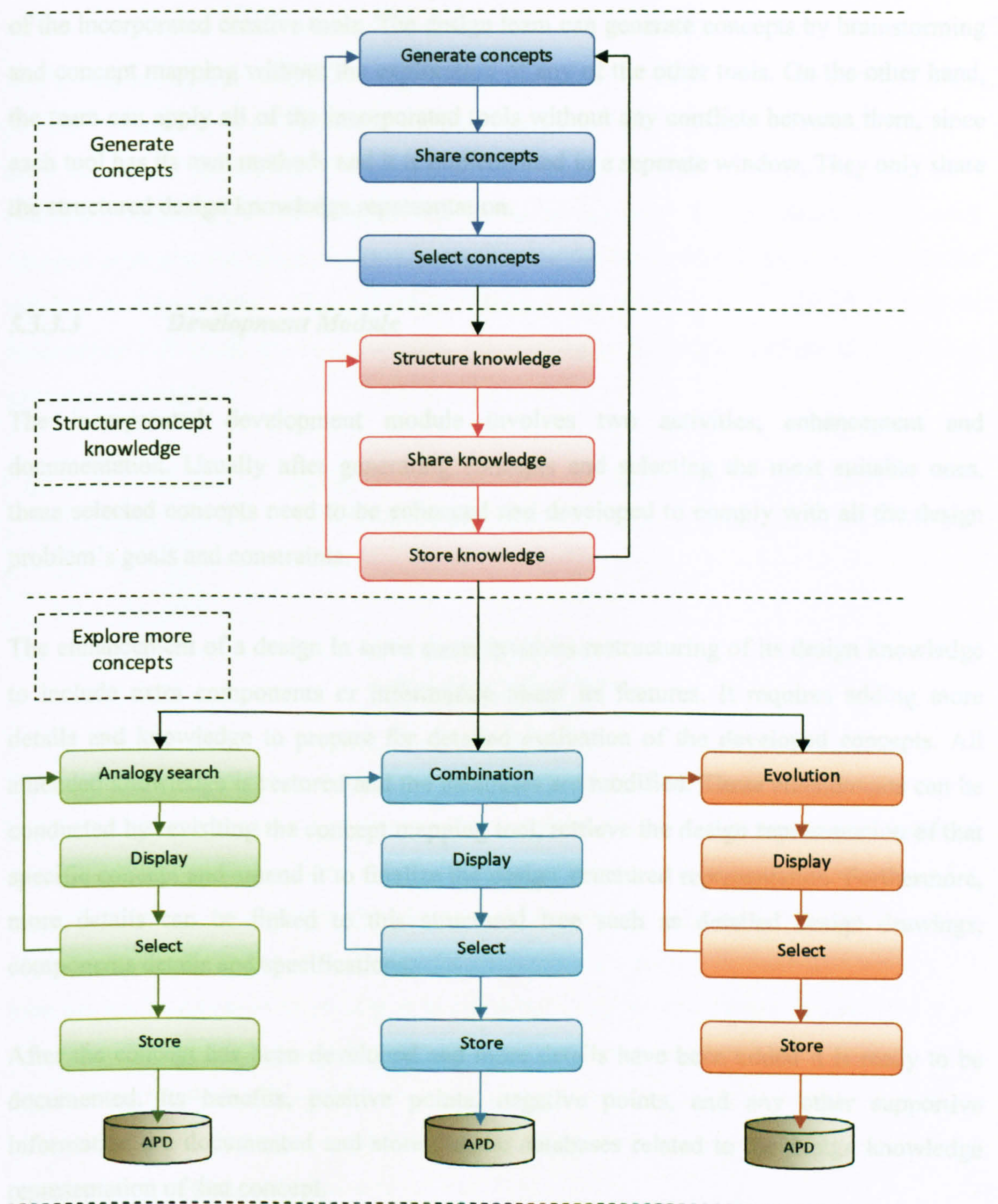


Figure 5.10 Computational activities of the concept generation module

This implemented approach has provided flexibility in applying and exploring one or more of the incorporated creative tools. The design team can generate concepts by brainstorming and concept mapping without the exploration of any of the other tools. On the other hand, the team can apply all of the incorporated tools without any conflicts between them, since each tool has its own methods and it is implemented in a separate window. They only share the structured design knowledge representation.

5.3.3.3 *Development Module*

The incorporated development module involves two activities; enhancement and documentation. Usually after generating concepts and selecting the most suitable ones, these selected concepts need to be enhanced and developed to comply with all the design problem's goals and constraints.

The enhancement of a design in some cases involves restructuring of its design knowledge to include extra components or information about its features. It requires adding more details and knowledge to prepare for detailed evaluation of the developed concepts. All amended knowledge is restored and the databases are modified. These amendments can be conducted by revisiting the concept mapping tool, retrieve the design representation of that specific concept and amend it to finalize the design structured representation. Furthermore, more details can be linked to this structured tree such as detailed design drawings, components details and specifications.

After the concept has been developed and more details have been added it is ready to be documented. Its benefits, positive points, negative points, and any other supportive information are documented and stored in the databases related to the design knowledge representation of that concept.

5.3.3.4 *Evaluation Module*

The evaluation module in the CDT system is designed to be used at any stage of the design process. Evaluation is always required, after the generation of ideas, to select the proper ones for future development. The process of evaluation has been divided into three correlated stages. The first stage is conducted at the level of individuals where each designer evaluates the generated concepts and saves the evaluation results in the system for retrieval at later stages. The individual designer can evaluate an unlimited number of alternatives and saves the results. Table 5.1 illustrates the table structure of evaluation stored in the database.

Designer ID	Concept code	Concept description	Concept image URL	Criterion (1) scores (Appropriateness)	Criterion (2) scores (Novelty)
101	001				
101	002				
101	003				

Table 5.1 Evaluation table

The second stage is team evaluation. The team evaluation is achieved by gathering all the individual evaluation saved earlier regarding a certain design alternative and calculate the average of their scores to get the team’s evaluation score. A multi criterion has been used in the CDT system to evaluate design alternatives. In order for a design to be creative certain objectives should be met. The two major objectives are appropriateness and novelty. To measure appropriateness of an idea it is evaluated using several factors. These factors are namely: achieving the required functions, achieving the required behaviours, and achieving required structures identified by the design team. The novelty of idea is measured based on how much the idea is new to the individual, the situation, or the society by introducing new functions, behaviours, and structures.

The third stage is named society evaluation because it includes specialists other than the design team. Therefore the society evaluation can include customers, other department's personnel, investors, suppliers and any other category of the society. This stage of evaluation explores how others view the design alternatives and if they are creative to them or not. This could provide a real world evaluation not only the designers' views.

The evaluation procedure is built on scaling controls. The evaluator needs to enter a score from 1-10 in reference to a certain criteria. The higher scores are positive while the lower scores are negative. For example if the usefulness of one idea is scored 9 out of 10, this means that the idea has a high score in usefulness and therefore it is very useful. On the contrary if the score is very low like 1 out of 10, the idea is evaluated as not useful or has a very little usefulness. Scoring is used in order to make calculations of the average evaluation result easier. Using excel tables the scores of all designers for a certain design alternative are stored in one single table. Each designer occupies one column with his/her scores regarding all the evaluation criteria incorporated. The average of each individual evaluation session is calculated and stored. Furthermore, the average of all the designers' evaluation sessions are calculated and stored in the same table. On the other hand society evaluation is stored in another table using the same criterion and the same layout. The result score calculated can be added to the previous evaluation table of designers to get a total average of the three stage evaluation processes.

This evaluation module is allowed to be used at all the various design processes. Evaluation is conducted after each process of concept generation to select the appropriate ones to continue the generation of new concepts or to develop further the selected ones. Furthermore, during the development process evaluation is needed to keep on checking if all objectives are achieved and all requirements are solved. This can also be the case in the detailed design where some issues could arise and require further reformulation of the problem. Figure 5.11 displays a brainstorming individual evaluation window.

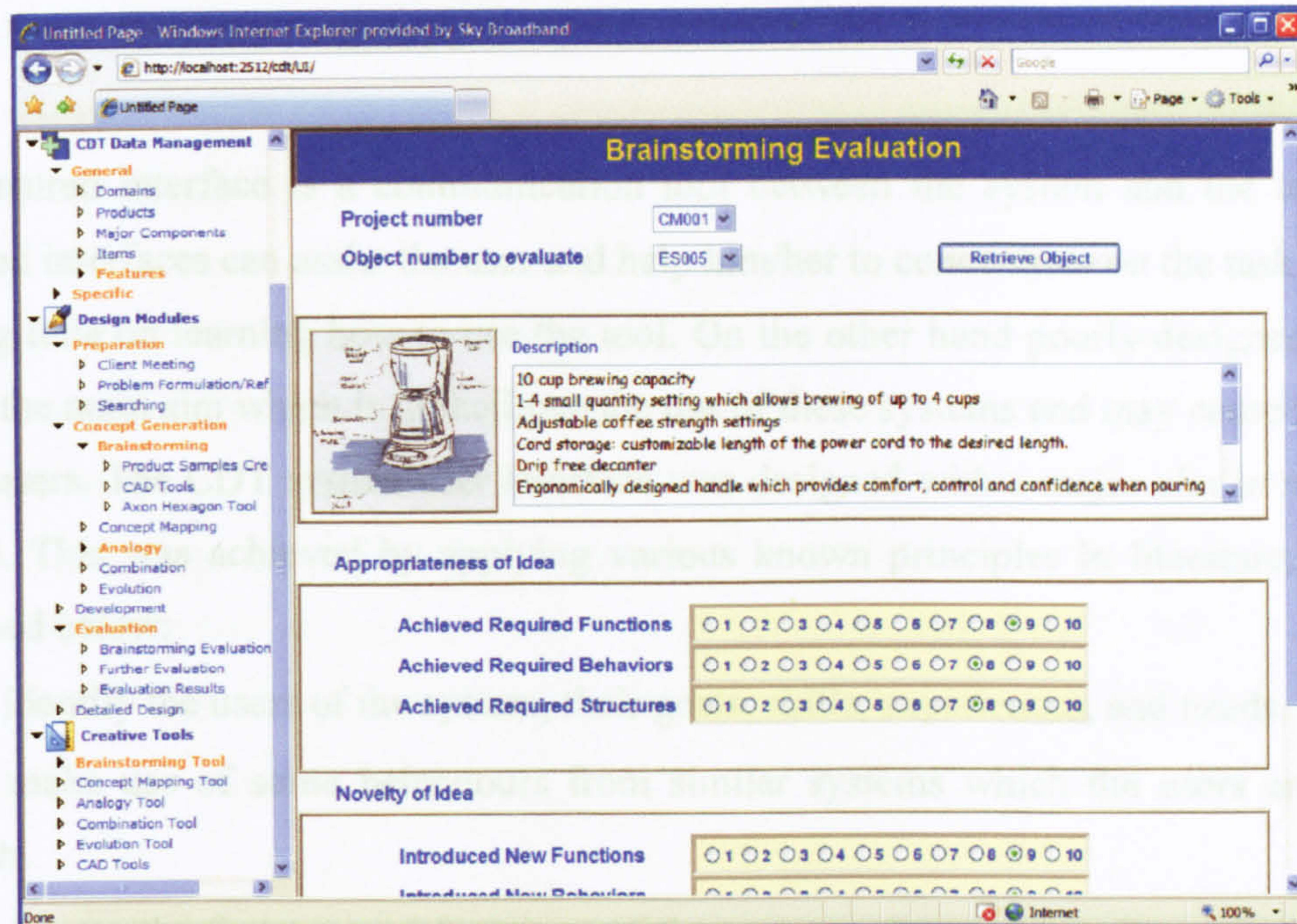


Figure 5.11 Brainstorming individual evaluation window

5.3.3.5 Detailed Design Module

Detailed design module involves the production of the final specifications, CAD drawings, and 3D models. This module has been supported in the developed CDT system by incorporating CAD and word processing applications to facilitate the creation of these detailed documents for the manufacturing process. It can be recognized that this final stage of the design process received minimum effort in developing this research because it is not directly related to the creative design thinking. It involves some technical presentation drawings and documents which do not influence the creative process much.

5.3.4 User-Centred Interface

User-centred interface is a communication tool between the system and the user. Well-designed interfaces can assist the user and help him/her to concentrate on the task instead of wasting time on learning how to use the tool. On the other hand poorly-designed ones can hinder the main aim which is to facilitate the use of these systems and may cause frustration to the users. The CDT system user interface was designed with a major aim in mind (*ease of use*). This was achieved by applying various known principles in literature, these are described below:

- To identify the users of the system, their goals, skills, experiences, and needs.
- To make use of some behaviours from similar systems which the users are familiar with.
- To expose the features and functions of the system when needed. For example the use of a tool bar is completely exposed, while the use of a dialog box is exposed by specific user command.
- Consistency of the system behaviour internally and externally. The system behaviours should make sense to other parts of that system and with the environment in which it runs like being compatible with user interface standards.
- Any change in the system behaviour should be reflected in the appearance of the interface.
- Determine the focal points where the user is required to focus his attention, because some features in the User Interface (UI) attract attention more than others which can cause distraction to the users in some cases.
- Provide shortcuts in getting a task done besides the concrete ways.
- Decide on the grammar of the UI if it is modal or non-modal for example the (Action-> Object) grammar is a modal one while the (Object-> Action) is a non-modal grammar.
- Incorporate different kinds of help that users need like descriptive, procedural, and navigational. The use of input validation tools is a way of providing help to the users.

- Give great emphasis to the aesthetic side of the UI by using design principles such as scale, proportion, balance, rhythm, emphasis, variety, contrast, and unity. The balance of these principles can produce a successful UI design.

The general page layout of the CDT system is shown in figure 5.12. In terms of the proposed system navigation, a tree view navigation scheme is employed to provide immediate access to major tools and modules of the CDT system. The tree view nodes provide quick access to each different part with the possibility of expanding the relevant nodes of the tree and collapsing the irrelevant ones for that specific task. This type of navigation provides the user with a holistic view of the system structural parts in one glance.

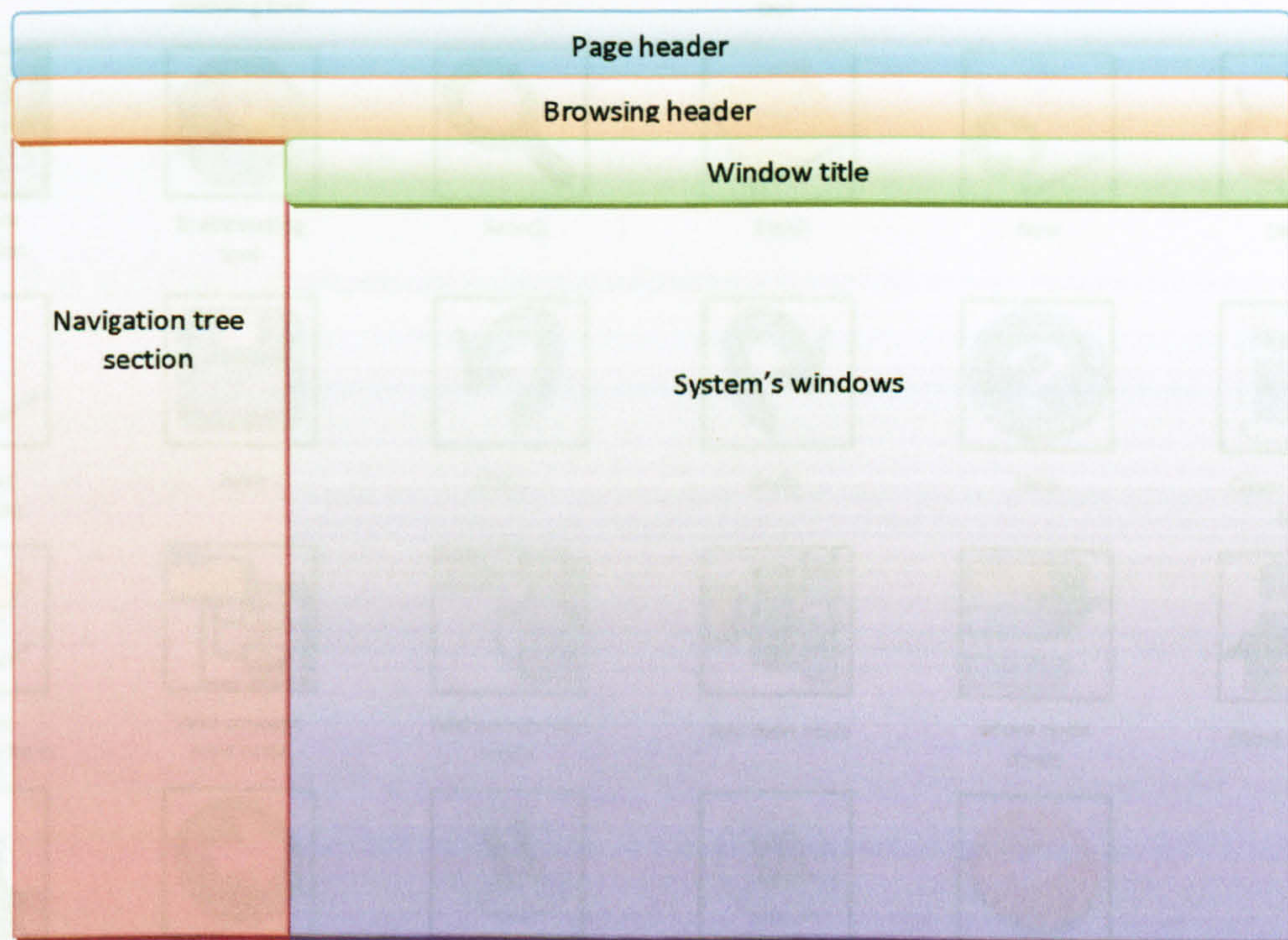


Figure 5.12 General layout of the CDT system page design

A variety of controls were used in the CDT system, some were used to display data to users such as data grid views in tabular form, and tree views in hierarchical form. Others were

used to collect data from users such as text boxes, drop down lists, radio button controls. Furthermore, text and image buttons were used in place of icons where each button displays a graphical image related to its function and accompanied by a tool tip when the user locates the mouse over it, so that the function of this button is clear to the user. Figure 5.13 displays some of the image buttons used in the CDT system with their tool tips. Therefore, various visualization formats and presentations of information such as graphical, tabular, verbal, and written communications were used.

In view of the UI architecture, design principles have been utilized in a balanced manner to get the best out of the system's design. For example moderate use of colours has been

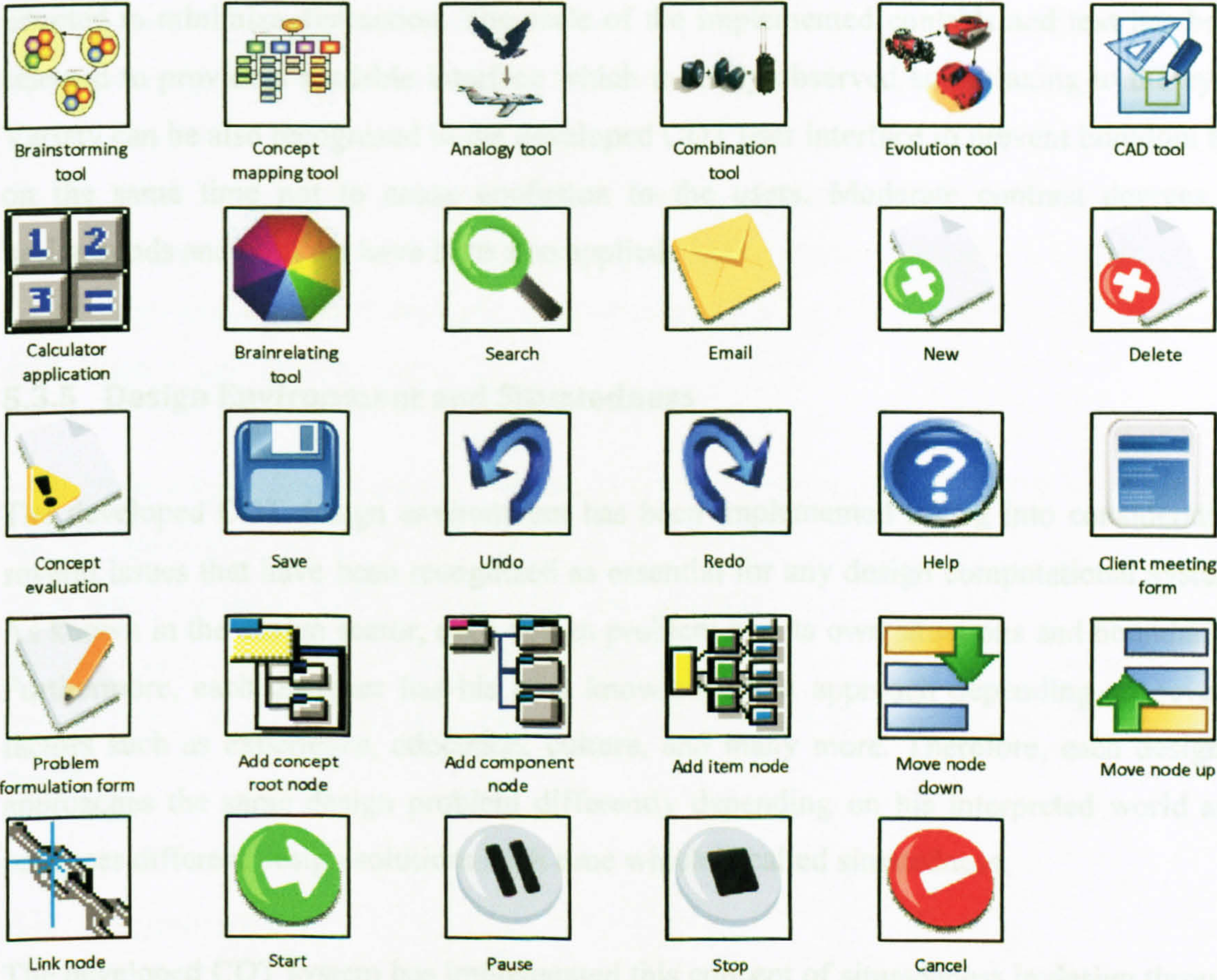


Figure 5.13 Image buttons in the CDT system

Several techniques have been applied in the developed CDT system to minimize the learning time of users such as tool tips describing the function of specific controls, and help windows explaining the system's procedures and describing specific parts of the system. Furthermore, different types of users' input validation tools have been incorporated such as required fields validates, range validates, and compare validates to eliminate any conflicts by entering the wrong data.

In terms of the UI aesthetics, design principles have been utilized in a balanced manner to get the best out of the system's layout. For example moderate use of colours has been adopted to minimize distraction. The scale of the implemented controls and text has been selected to provide a readable interface which is easily observed and relaxing to the eyes. Variety can be also recognized in the developed CDT user interface to prevent boredom but on the same time not to cause confusion to the users. Moderate contrast degrees in backgrounds and controls have been also applied.

5.3.5 Design Environment and Situatedness

The developed CDT design environment has been implemented taking into consideration several issues that have been recognized as essential for any design computational system. As known in the design sector, each design problem has its own situations and boundaries. Furthermore, each designer has his own knowledge and approach depending on several factors such as experience, education, culture, and many more. Therefore, each designer approaches the same design problem differently depending on his interpreted world and produces different design solutions each time which is called situatedness.

The developed CDT system has implemented this concept of situatedness in design through its flexible interaction between the designer's individual environment, the designers' team environment, and the identified design problem environment. Furthermore, it has provided

tools and procedures for the designers to explore more creative solutions through better interaction between the previously described environments.

The developed CDT system facilitates the expansion of its design environment through its incorporated procedures, tools, and technologies. The individual designer can expand his repository of knowledge through search and exploration. Each time the designer uses the system he/she is exposed to new design knowledge which enforces his/her environment. Similarly, sharing each individual's design knowledge through storing it in the databases and viewing it by all the authorized users expands the designers' team environment. Furthermore, each individual designer can modify and expand the design problem's environment by adding new knowledge which is reflected to all users.

On the other hand, each time the designer uses the system to create new solutions, the databases are expanded and more design knowledge is created. Therefore, the developed CDT design environment is designed and implemented to be expanded regularly through its application to new design problems.

This expansion and the interaction between the various environments require a constructive design knowledge repository or memory. In the CDT system the flexibility of the knowledge databases which can be changed, amended, updated, at any time during the design process represents the concept of constructive memory. Any time a need arises for a new memory, it will be added to the system's knowledge and will be part of the design environment.

5.4 Summary

This chapter discussed the design computational model of the CDT system. A detailed description of the developed design knowledge computation including the design knowledge representation and the design knowledge database management has been

presented. The computation of the incorporated creative tools has been described comprehensively in relation to the design processes they are part of. Furthermore, the incorporated various design modules have been illustrated by discussing the various activities they encompass. Moreover a full description has been given in relation to the user interface of the CDT system such as the principles and the various features used. In the final section a discussion of the CDT design environment and situatedness in design and how they were implemented in the CDT system has been explained.

The previously presented CDT design computational model has the following features:

- An integrated flexible design environment which achieves a high level of interaction between its various elements and the designers through its user friendly interface and its embedded techniques.
- A well structured design knowledge representation which is constructed by designers themselves through the CDT system interface using the identified knowledge and incorporated tools.
- Constructive knowledge databases which can be extended after each design problem and through the whole design process.
- The integration of state of the art creative design tools which achieve better exploration of creative design solution through its embedded methods.
- The incorporation of design modules which provide guidance to designers in order to solve complex design problems through its integrated activities.
- The broad applicability of the CDT system to involve any design sector and various cultures and backgrounds because it can be accustomed to any design problem, society ,and culture depending on the design knowledge identified and stored in the databases provided by the designers.
- It provides a step forward to bridge the gap between designers and computer technology. A proof that designers are in control of all computer tools and not the other way around.

CHAPTER SIX

A PROTOTYPE CREATIVE DESIGN TOOLS SYSTEM

6.1 Overview

This chapter illustrates the details of the implementation of the CDT system. The developed CDT system presents a creative design environment designed and implemented to support creative design problem solving through the integration of various elements; design knowledge, design processes, and creative tools. These elements are integrated within a flexible collaborative design environment to support design teams' creative thinking. The implementation of these integrated elements is discussed in this chapter. The various design modules encompassed in the system are represented through system scenarios. The technologies adopted to implement the system are described. Moreover, the implementation of the developed design knowledge representation and the various databases is demonstrated. Furthermore, the implementation of the various incorporated creative tools is verified and the design consistency of the implemented CDT system is discussed at the end of this chapter.

6.2 Introduction

A comprehensive computational model for the developed CDT system has been presented in CHAPTER FIVE. This CDT computational model provides a detailed description of the methods and procedures of its incorporated elements; design modules, design knowledge, and creative tools to be implemented. The developed CDT computational model has been implemented as a web application using new advanced computer technologies. This chapter aims to present the techniques and technologies utilized to implement the developed CDT computational model.

The implementation of the incorporated design modules of the CDT system are illustrated through system scenarios. Each module has its own structure and utilizes different types of

tools and visualization displays to apply its methods and accomplish its activities. Therefore a separate scenario is illustrated for each design module to explain in detail the implementation of its structure and the procedures to accomplish its activities.

Design knowledge representation plays an important role in successful application of the creative tools and the design modules incorporated in the CDT creative environment. A detailed structured hierarchical design knowledge representation has been developed and presented in CHAPTER FIVE. The generic design representation structure is embedded within the system to provide the base for the design team to identify the relative design knowledge without any conflict with the embedded methods or activities. The design team identifies new design knowledge through the user interface of the CDT system using the creative tools and the design modules incorporated and store it in the relative databases which are a major part of the CDT system. The structuring of design knowledge and the implementation of the different incorporated databases are detailed through discussing the developed procedures to identify new design knowledge and the relations created between the tables of the databases to create this design knowledge structure.

The incorporated creative tools and its computational methods constitute a major part of the CDT system implementation. Each tool has its own methods and activities to be accomplished to explore more design solutions to the design problem. The interaction between the design team and these tools is considered very important in the CDT system and has been taken into consideration in its implementation. The creative tools are to support the designers not to replace them. Therefore, these tools have been implemented to conduct its activities based on the designers input, selections, and the design problem situation.

Therefore, a human-centred approach is considered vital in the early stages of the design process where the most creative ideas are generated. Through the use of proper environments where knowledge is structured according to design situations, and processes and tools are applied efficiently to explore more creative solutions by broadening the

creative solution space, more creative design solutions can be achieved in minimal lead time to be detailed for manufacturing.

A full proper implementation of the proposed CDT system provides state of the art holistic flexible environment to enhance creative thinking in various design disciplines, which is a major contribution in the creative design research. The previously mentioned research work in the literature lacks that holistic approach of such systems. Furthermore, the implementation of the CDT system as a web application offered many advantages over other systems summarized as follows:

- Web applications provide easy accessibility for all users wherever they are located. As long as they have internet connection they can connect and use the system.
- The consistency of design knowledge that designers have access to because any change in the design knowledge during the design process is shared by all users at the same time.
- Collaboration can be more efficient through the direct access to knowledge to overcome the disadvantages of the synchronous ways of collaboration if the users are located in geographical areas with time differences. Therefore having direct access to the stored knowledge can provide faster response for collaboration with no time zone issues.
- System updates are reflected immediately to all users and is conducted at one single station which will minimize the cost and time spent on updating processes.

The implementation of the CDT system allows the validation of the holistic approach proposed by applying a case study using the developed prototype. It provides the chance to review the developed design representations and their application in the various incorporated tools. Furthermore, it offers a test case to check on the tools' usefulness and efficiency in creative design thinking. A comprehensive realistic viewpoint can be attained by testing the system with some real design problems to come up with conclusions and decide on the future work to be conducted at later stages.

6.3 System Scenario

The CDT system scenario detailed in figure 6.1 starts by defining the design problem space through applying various activities such as meeting clients and conducting relative searches. This includes identification of the problem's goals, requirements, and constraints. This defined problem space can be modified each time a new knowledge evolves to adjust the problem's situation. Identification of new design knowledge is usually conducted by the design team in two stages. The first stage is at the preparation module where designers identify general and specific knowledge for the design problem to support its situation as illustrated in figure 6.2. The second stage is at the concept generation module when the designers start generating and exploring more design concepts. Designers are provided with the proper means to identify and store new knowledge in the incorporated databases, which in turn, can be part of the design problem situation and can be utilized by all the integrated elements of the system.

The generation and exploration of design concepts starts with the concept generation module as illustrated in figure 6.3. Various tools have been incorporated to achieve both tasks of generation and exploration. Two divergent-convergent thinking approaches have been developed and implemented in this module. The generation of design concepts has been developed to apply a single divergent-convergent thinking approach at first. Brainstorming and concept mapping tools are the active ones for this task. Designers brainstorm to generate as many concepts as possible individually without any criticism or evaluation of any sort. These generated concepts are structured hierarchically through the application of the concept mapping tool. At later stages, the designers evaluate the generated concepts of all the design team members to select the most suitable ones for exploration.

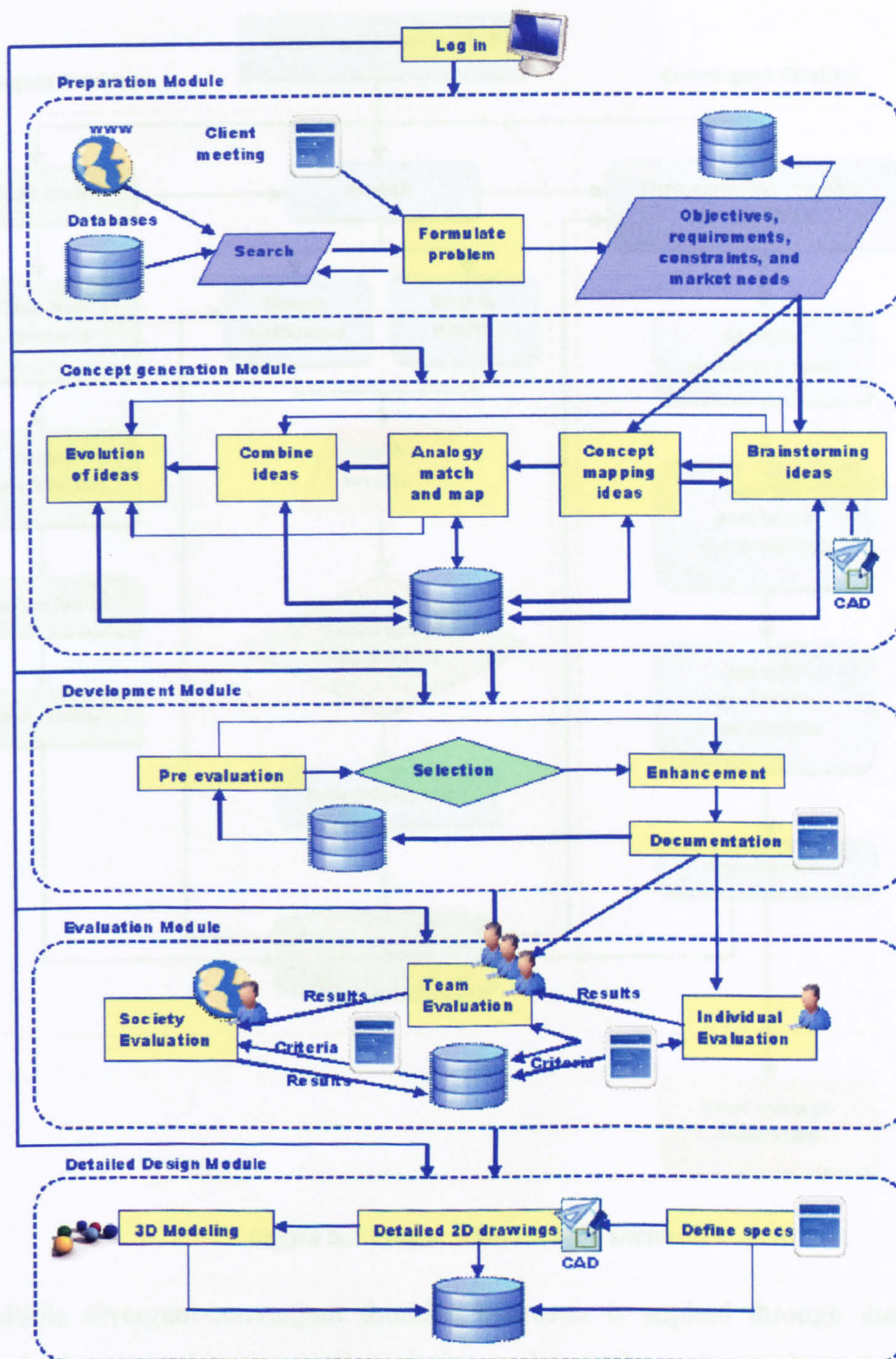


Figure 6.1 CDT system scenario

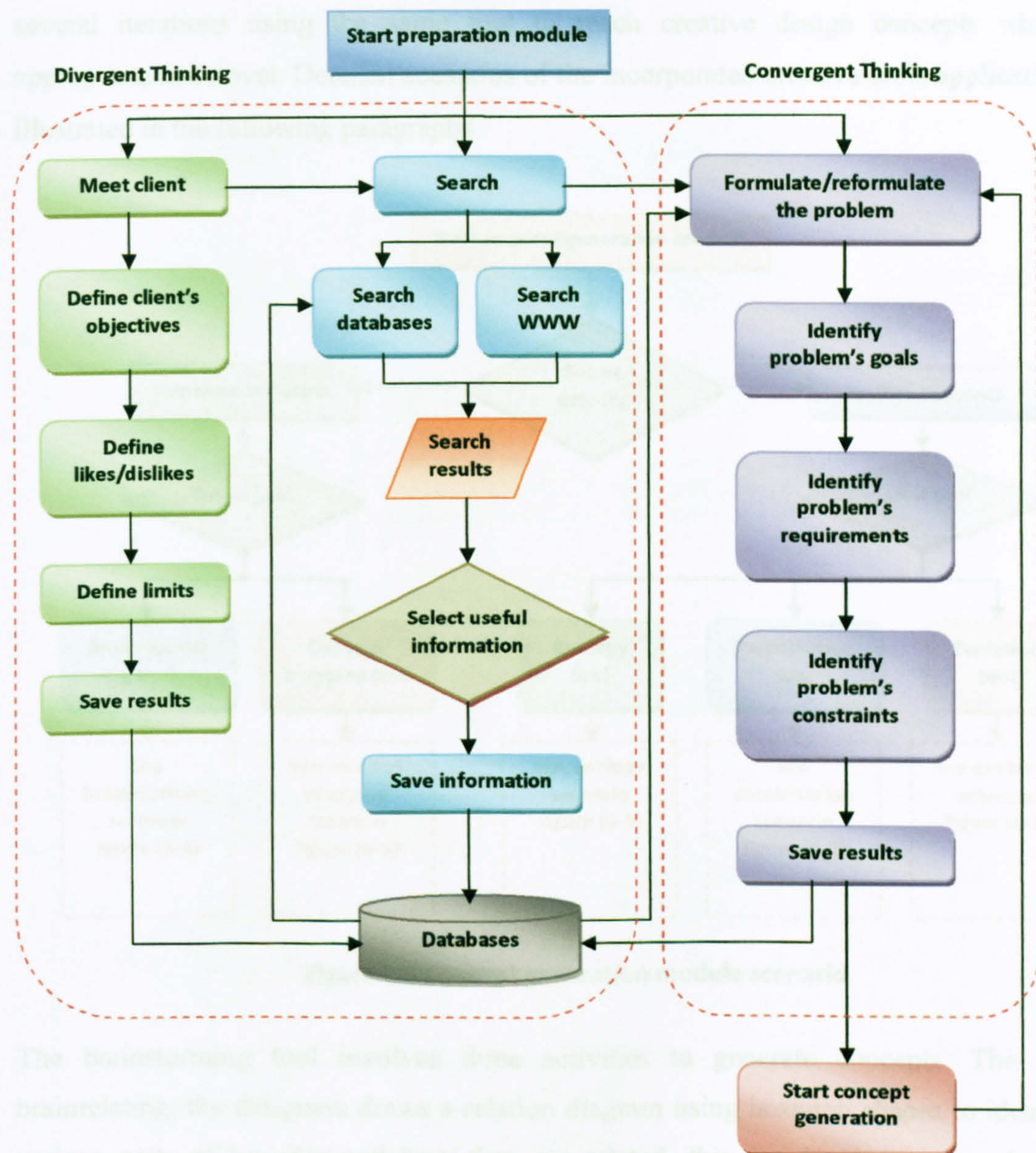


Figure 6.2 Preparation module scenario

A multiple divergent-convergent thinking approach is applied through the exploration stage. Analogy, combination, and evolution tools are the active tools at this exploration activity. The designer chooses the methods to apply in each tool and selects the design concepts to use for exploration. Each time results are displayed, the designer selects few options to proceed with the same tool or to activate another tool. Therefore, it may take

several iterations using the same tool to reach creative design concepts which are appropriate and novel. Detailed scenarios of the incorporated creative tools applications are illustrated in the following paragraphs.

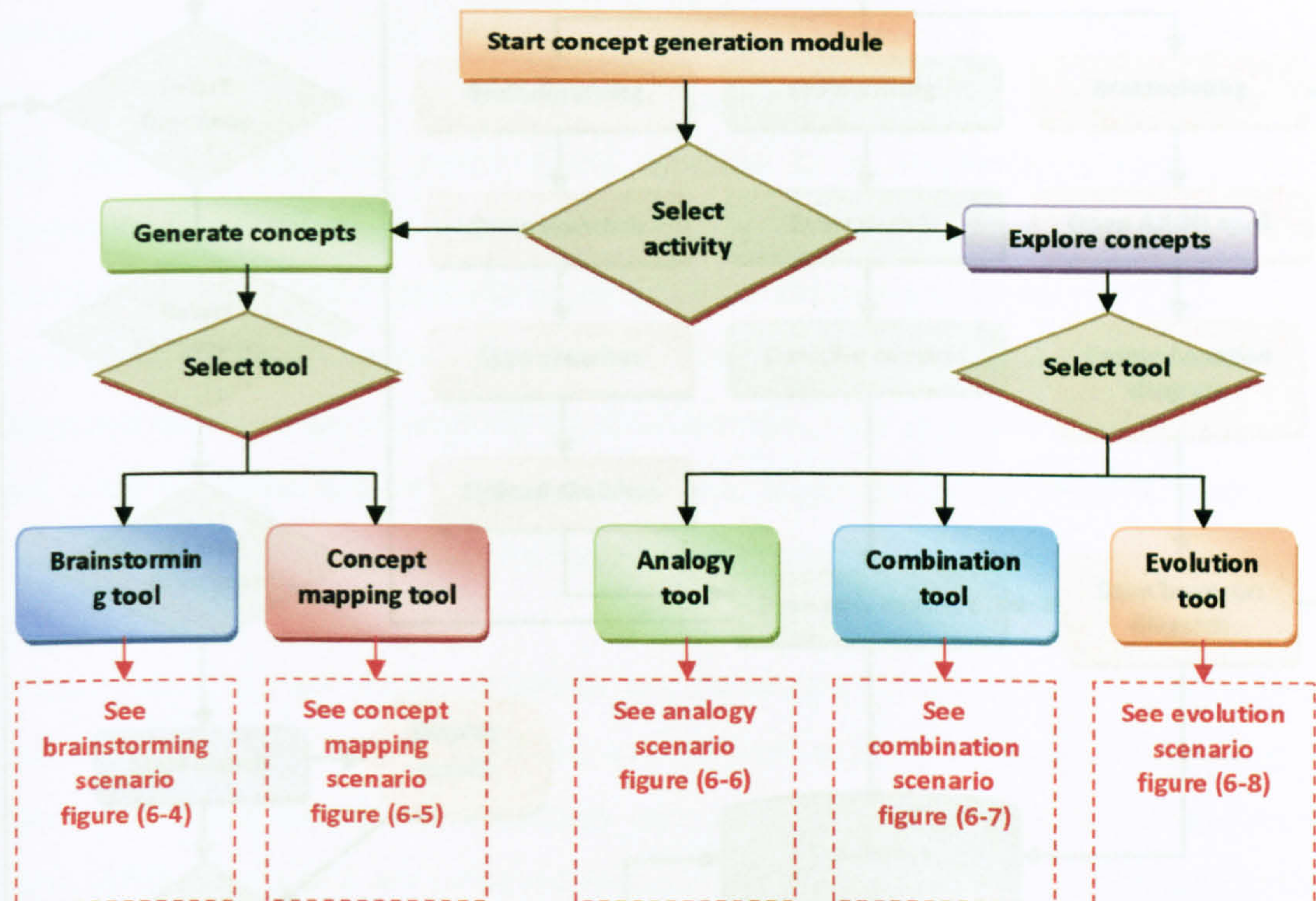


Figure 6.3 Concept generation module scenario

The brainstorming tool involves three activities to generate concepts. The first is brainrelating; the designers draws a relation diagram using hexagon shapes to identify the various parts of his idea and how they are related, this can be done using Axon2008 commercial tool which is integrated with the CDT system. The second activity is brainsketching; the designer sketches his ideas either using conventional ways or computer tools and stores them in the computer. Then the designer retrieves the sketch and relates it with the proper description which is called brainwriting to describe his /her idea verbally. The generated idea is then stored in the proper database to be retrieved, evaluated, and developed at later stages. Figure 6.4 illustrates the brainstorming tool application scenario.

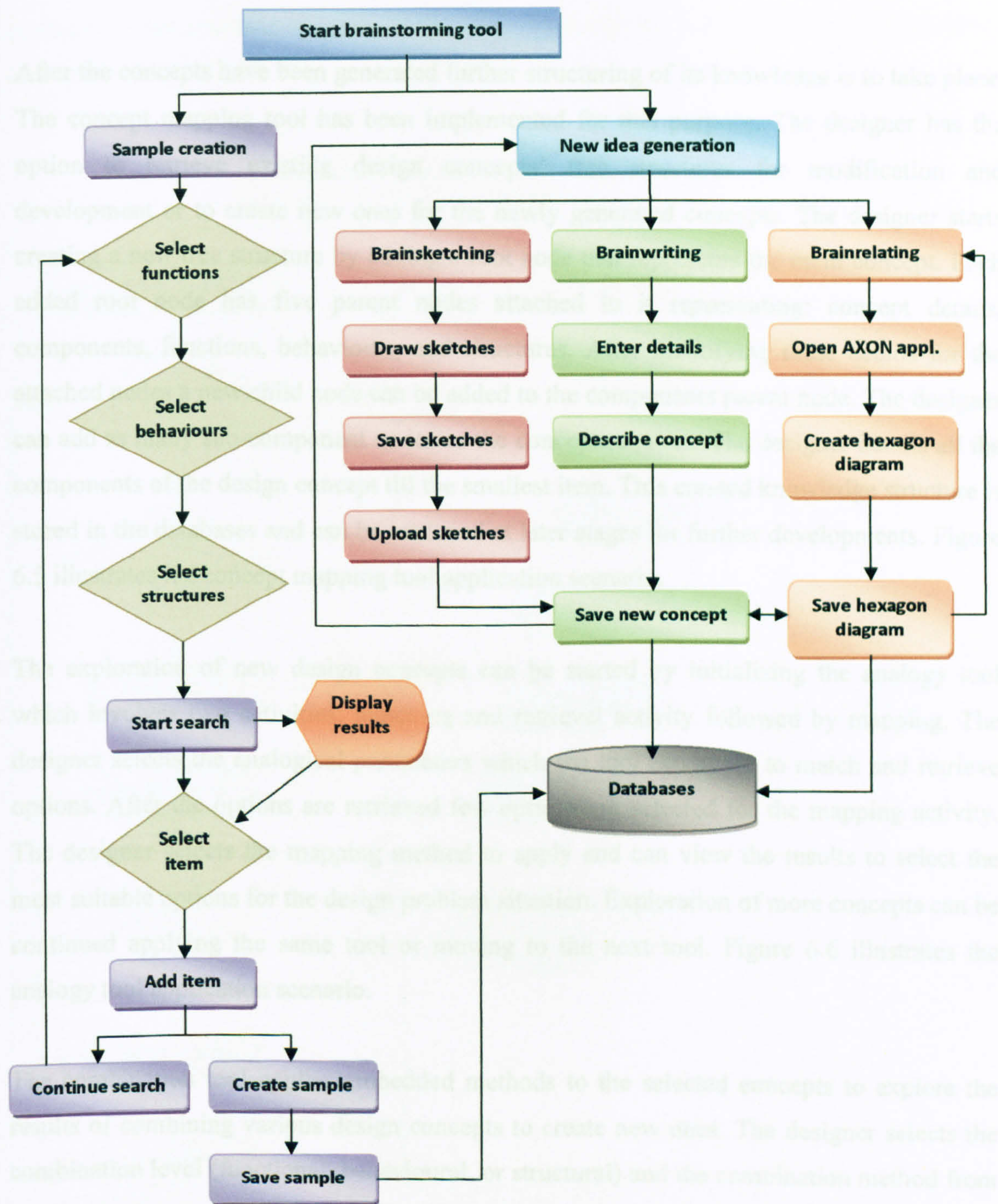


Figure 6.4 Brainstorming tool scenario

After the concepts have been generated further structuring of its knowledge is to take place. The concept mapping tool has been implemented for this purpose. The designer has the option to retrieve existing design concepts' tree structures for modification and development or to create new ones for the newly generated concepts. The designer starts creating a new tree structure by adding a root node that represents the main concept. Each added root node has five parent nodes attached to it representing; concept details, components, functions, behaviours, and structures. After identifying these details for the attached nodes a new child node can be added to the components parent node. The designer can add as many sub-component nodes as the concept requires. The designer details all the components of the design concept till the smallest item. This created knowledge structure is stored in the databases and can be retrieved at later stages for further developments. Figure 6.5 illustrates the concept mapping tool application scenario.

The exploration of new design concepts can be started by initializing the analogy tool which involves two activities; matching and retrieval activity followed by mapping. The designer selects the analogical parameters which the tool can apply to match and retrieve options. After the options are retrieved few options are selected for the mapping activity. The designer selects the mapping method to apply and can view the results to select the most suitable options for the design problem situation. Exploration of more concepts can be continued applying the same tool or moving to the next tool. Figure 6.6 illustrates the analogy tool application scenario.

The combination tool applies embedded methods to the selected concepts to explore the results of combining various design concepts to create new ones. The designer selects the combination level (functional, behavioural, or structural) and the combination method from the four types provided: systematic combination, tree random combination, vertices random combination and total random combination. Afterward, the combination results are displayed and the designer selects the most creative combined concepts according to his individual evaluation. The designer can apply as many combinations to explore creative

concepts as the situation requires. Figure 6.7 illustrates the combination tool application scenario.

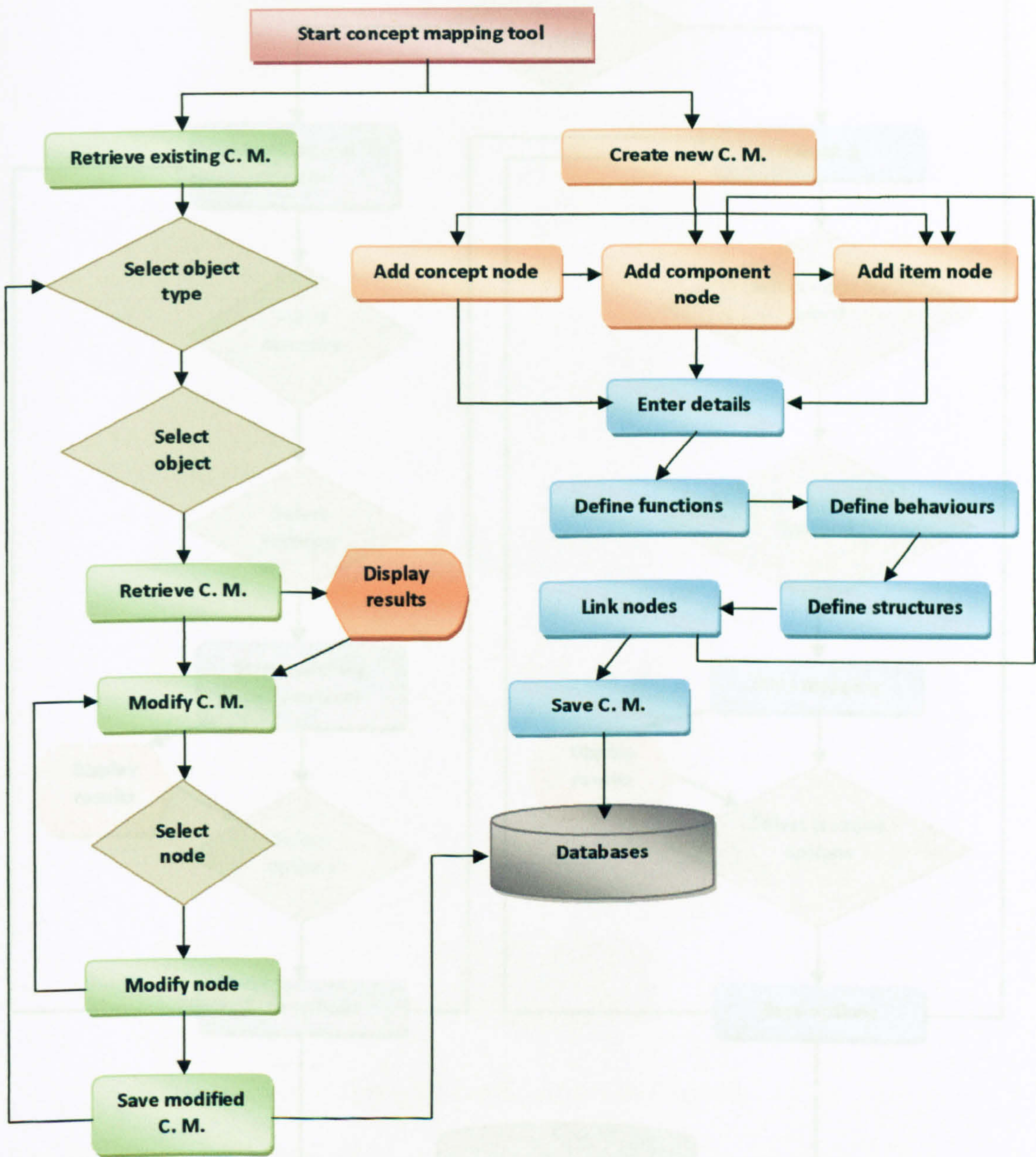


Figure 6.5 Concept mapping tool scenario

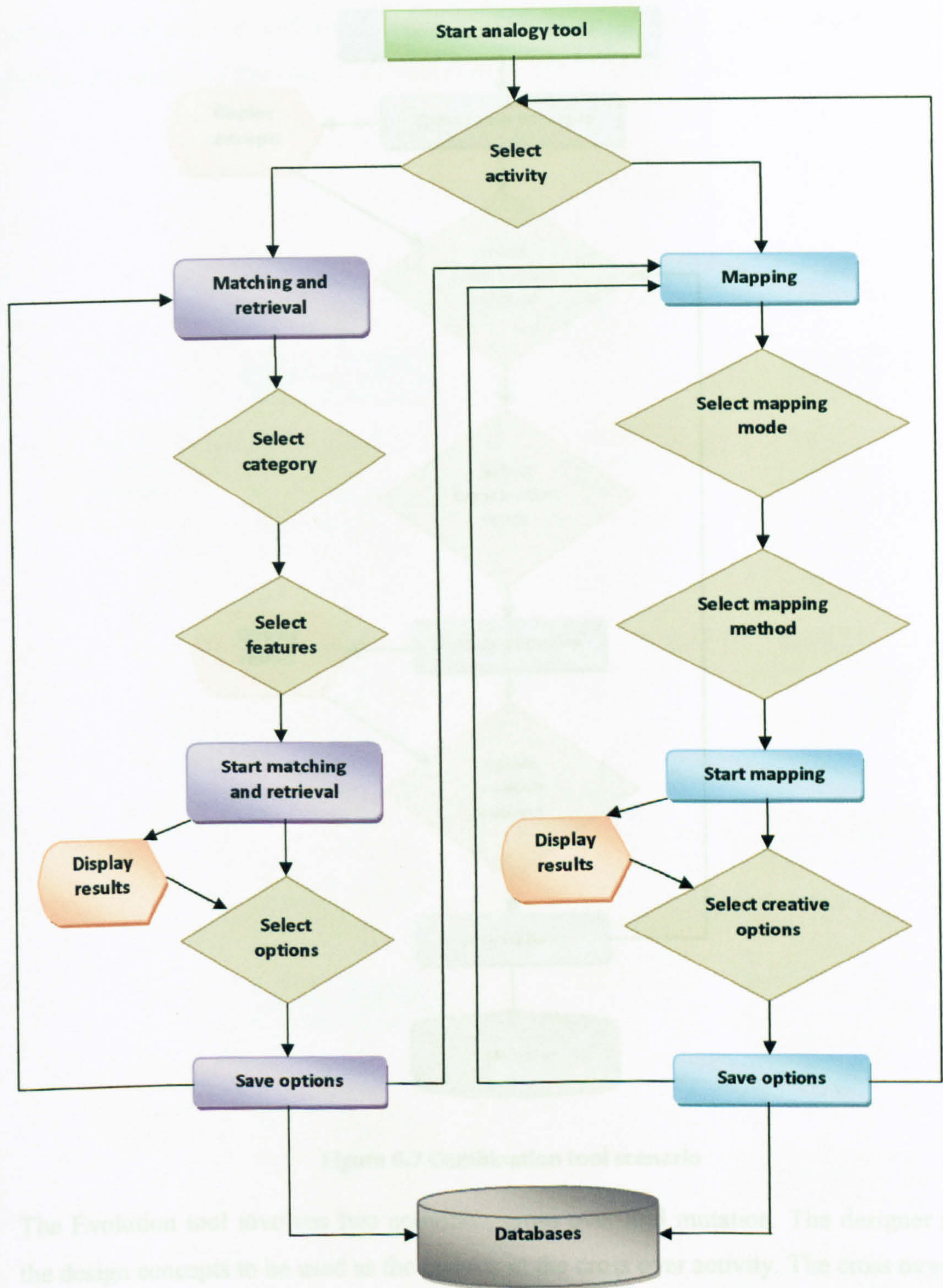


Figure 6.6 Analogy tool scenario

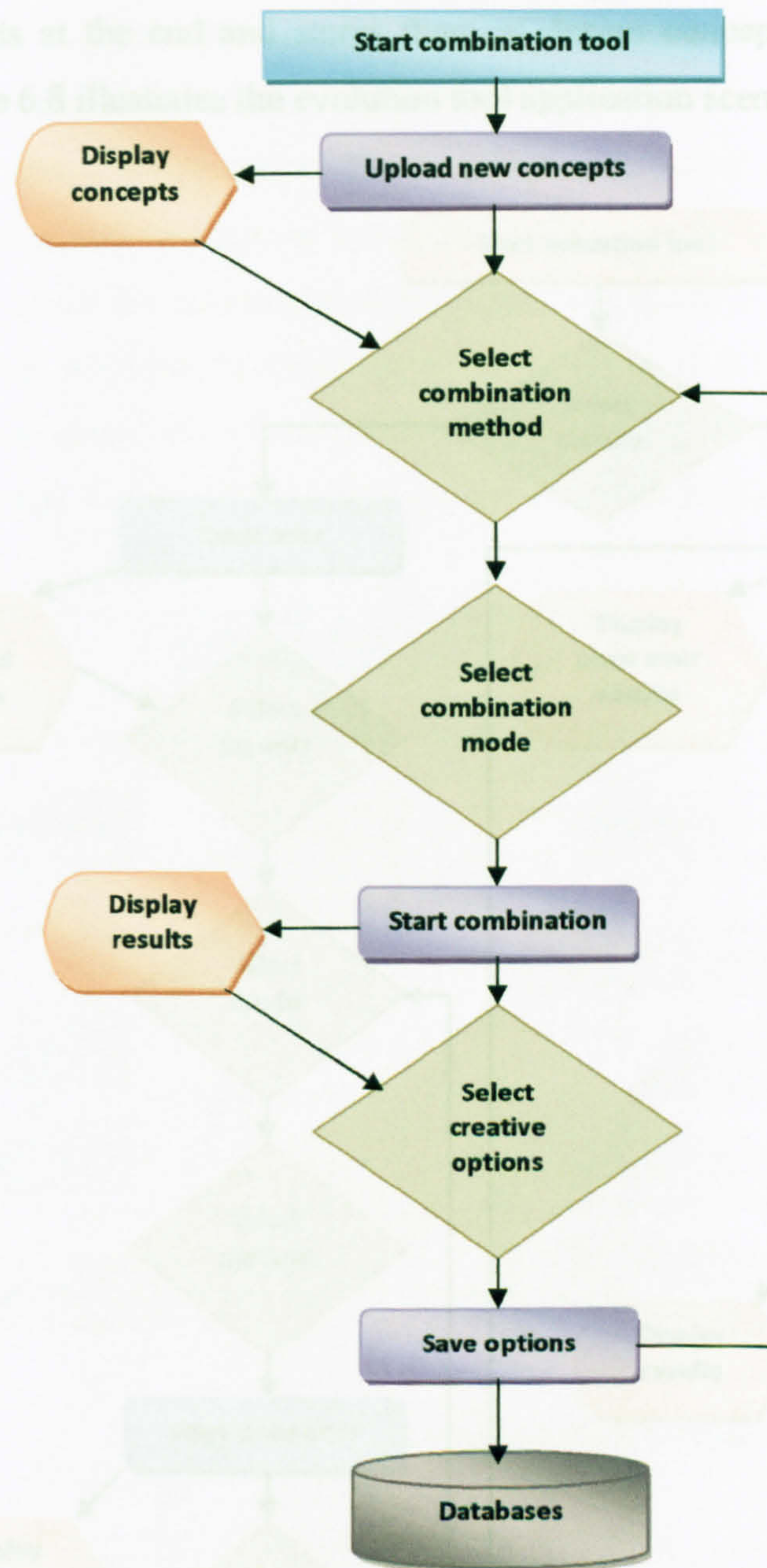


Figure 6.7 Combination tool scenario

The Evolution tool involves two activities; cross over and mutation. The designer selects the design concepts to be used as the parents in the cross over activity. The cross over result is displayed to let the designer select the parents for the next activity. More cross over can be activated or mutation of the generated results is conducted. The designer selects the most

creative results at the end and stores them as design concepts which can be developed further. Figure 6.8 illustrates the evolution tool application scenario.

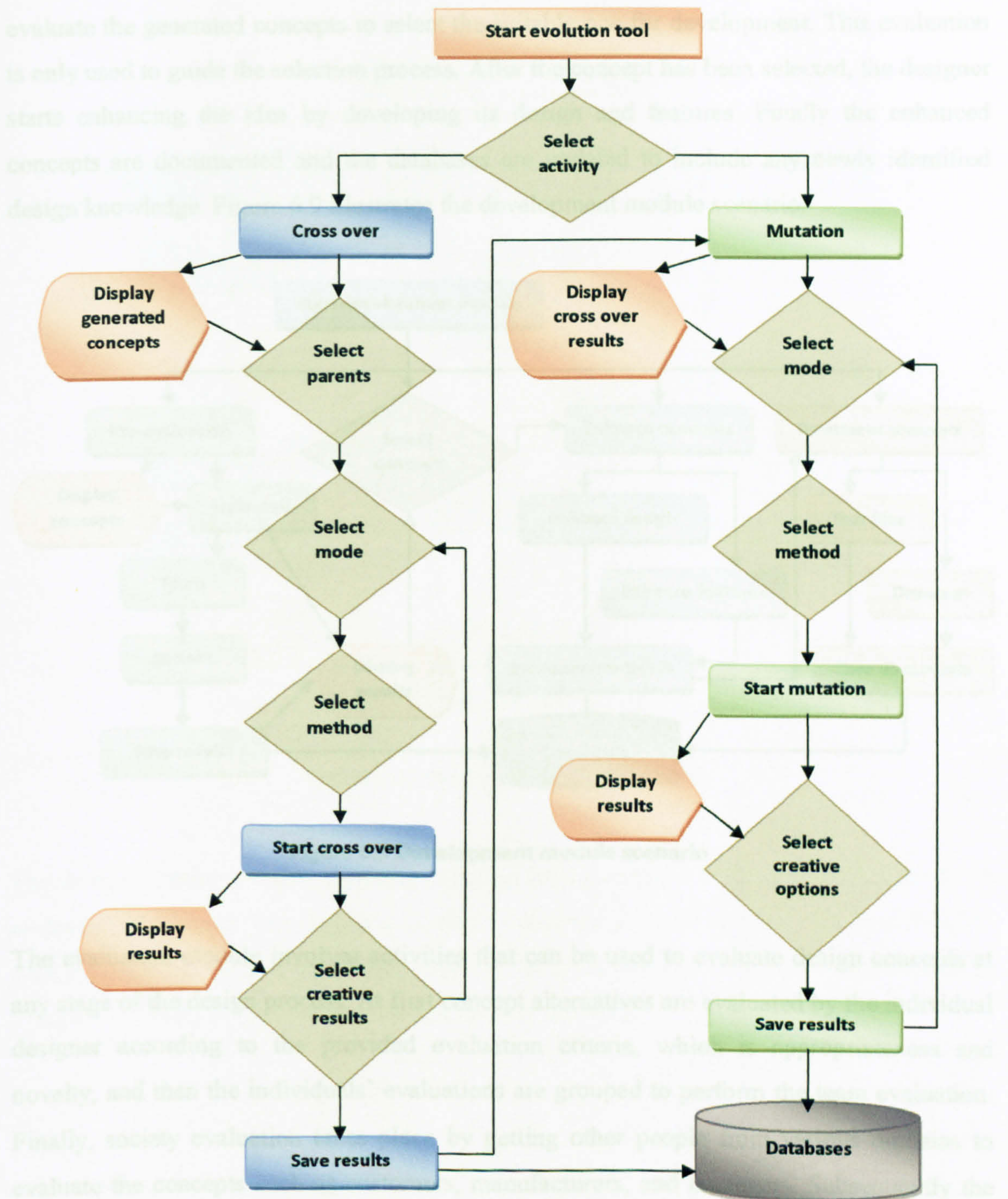


Figure 6.8 Evolution tool scenario

After achieving a good resource of concept alternatives, development of these options begins. The development module involves four activities namely: pre-evaluation, selection, enhancement, and documentation. For a designer to select a concept, he/she needs to evaluate the generated concepts to select the suitable one for development. This evaluation is only used to guide the selection process. After the concept has been selected, the designer starts enhancing the idea by developing its design and features. Finally the enhanced concepts are documented and the databases are updated to include any newly identified design knowledge. Figure 6.9 illustrates the development module scenario.

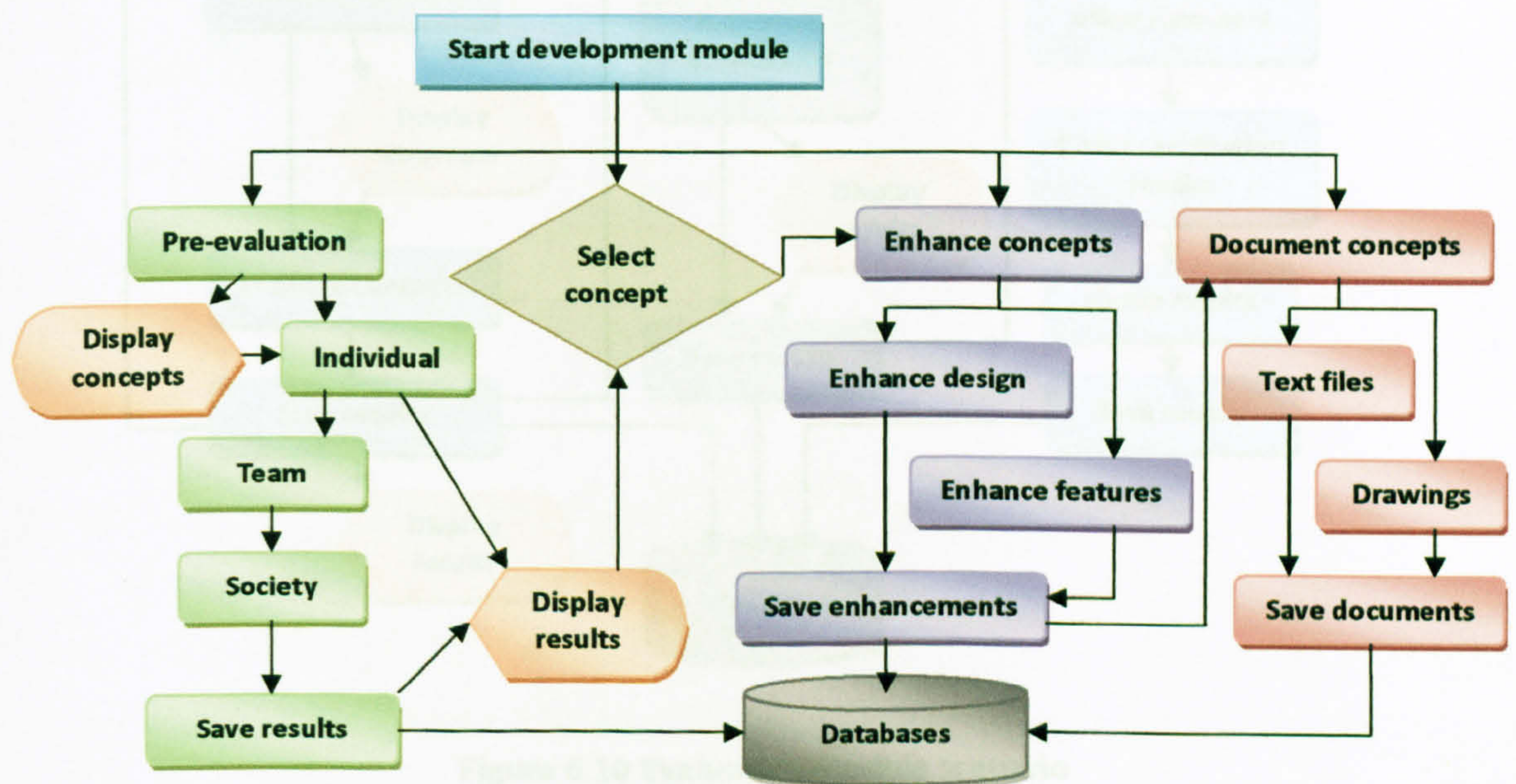


Figure 6.9 Development module scenario

The evaluation module involves activities that can be used to evaluate design concepts at any stage of the design process. At first concept alternatives are evaluated by the individual designer according to the provided evaluation criteria, which is appropriateness and novelty, and then the individuals' evaluations are grouped to perform the team evaluation. Finally, society evaluation takes place by getting other people from various domains to evaluate the concepts such as customers, manufacturers, and managers. Subsequently the

results are displayed again to the team to reach a final decision based on the accumulated evaluation results achieved. Figure 6.10 illustrates the evaluation module scenario. The chosen concepts are then finalized and detailed.

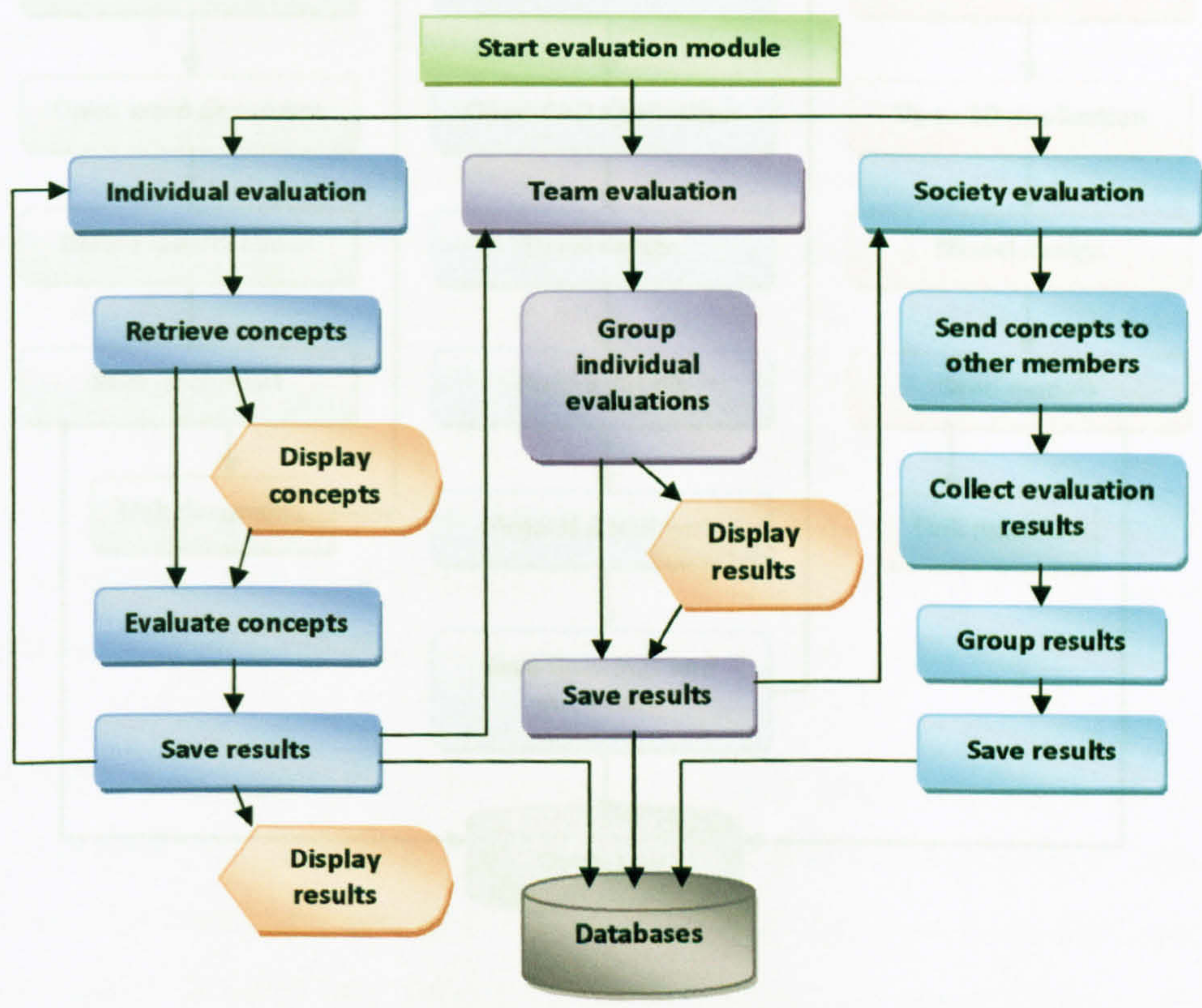


Figure 6.10 Evaluation module scenario

The detailed design module supports detailing of the selected concepts which have been evaluated as creative. The detailing involves definition of specifications, the final detailed drawings, and 3D models. After this stage the design is ready to be sent for manufacturing. Figure 6.11 illustrates the detailed design module scenario.

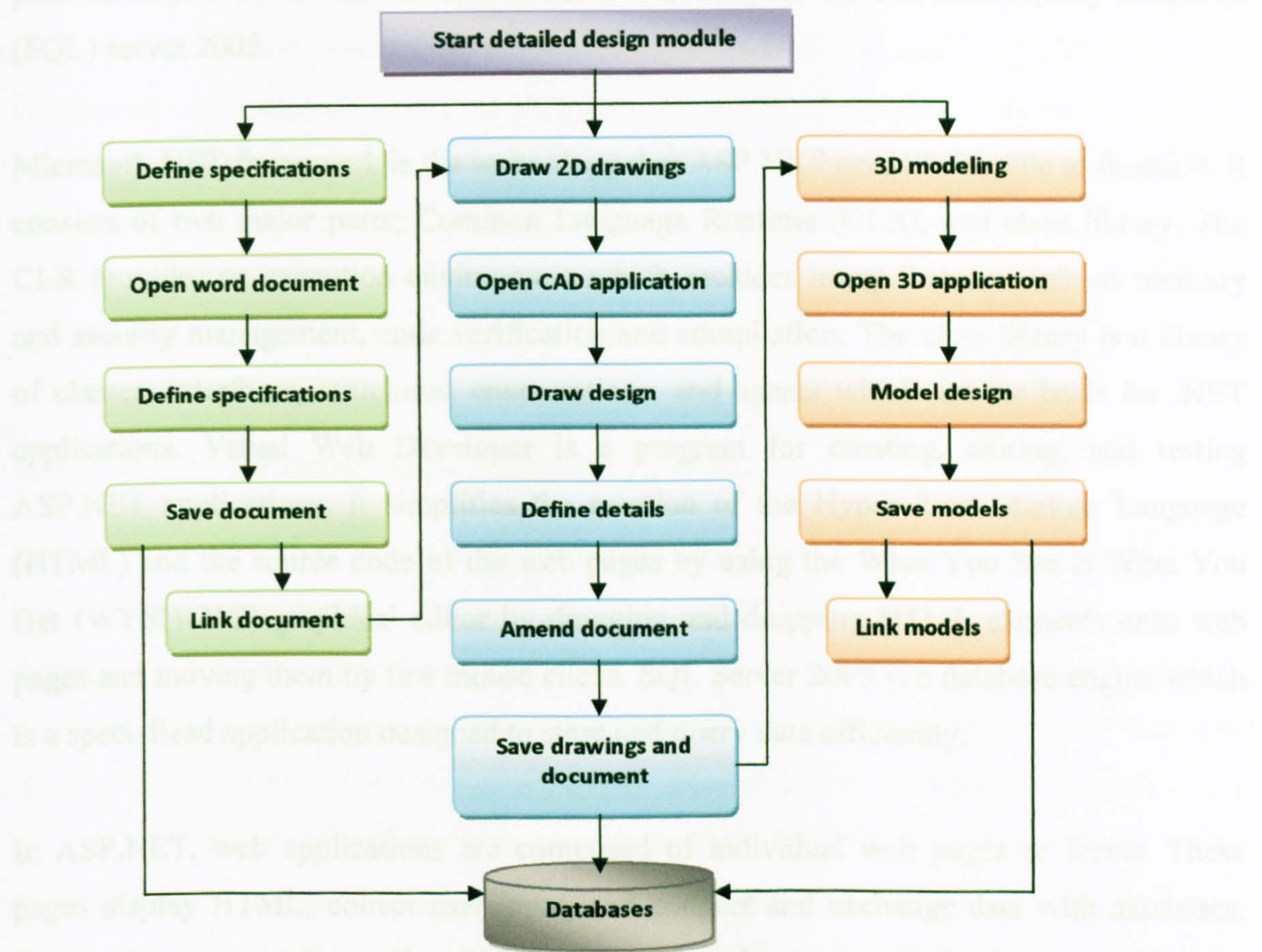


Figure 6.11 Detailed design module scenario

6.4 System Implementation Technology

Recent advances in computation and the World Wide Web technologies provided the base for the implementation of the proposed system. The developed CDT system has been implemented using Microsoft's ASP.NET web programming technology. This technology provided an easy platform to achieve the creation of data driven dynamic web applications with the minimal effort compared to other available technologies. The Microsoft visual studio 2005 tool which has been used to develop the CDT system incorporates three major

parts namely: the .NET framework, visual web developer, and Structured Query Language (SQL) server 2005.

Microsoft .NET framework is the technology that ASP.NET needs to be able to function. It consists of two major parts; Common Language Runtime (CLR), and class library. The CLR provides an execution environment which includes many features such as memory and security management, code verification and compilation. The class library is a library of classes, interfaces, structures, enumerations, and agents which are the basis for .NET applications. Visual Web Developer is a program for creating, editing, and testing ASP.NET applications. It simplifies the creation of the Hyper Text Markup Language (HTML) and the source code of the web pages by using the What You See is What You Get (WYSIWYG) graphical editor by dragging and dropping HTML elements onto web pages and moving them by few mouse clicks. SQL Server 2005 is a database engine which is a specialized application designed to store and query data efficiently.

In ASP.NET, web applications are composed of individual web pages or forms. These pages display HTML, collect user input, and connect and exchange data with databases. Each web page contains a mix of HTML markup and source code. In the source code the more advanced features are programmed. A number of programming languages are supported by Microsoft visual studio namely: Visual Basic, C#, C++, and Visual J#. The Visual Basic language has been selected for the implementation of the CDT system.

Furthermore, Visual Web Developer includes a light weight web server to host and test web pages locally. This can eliminate the need for a web server to be installed on the machine while developing the web application. This local hosting of ASP.NET has various advantages throughout the web application development. The testing can be done while offline, no need to be connected to the internet, moreover it is faster because there are no requests made over the internet. Another advantage is the advanced debugging such as stepping through running code line by line.

The application of web-based technologies in design systems has several advantages. It overcomes the geographic factors between designers through its easy accessibility and the consistency of design knowledge it provides. Web applications provide the same experience for all users. Furthermore, the updates of the applications are reflected to all users which will minimize the administration time and cost of such applications updates. Any changes in the data are reflected immediately to all users at any locations which should enhance collaboration among design team members.

6.5 *Design Knowledge Representation*

The developed design knowledge representation described in CHAPTER FIVE is implemented using the tree view control in the ASP.NET environment. The tree view control is one of the navigation controls that can be connected to the databases or SQL documents. Since the data required is stored in the databases the connection has been achieved with the related databases to store the data using the hierarchical structure of the tree views. Each node in the tree is related to a certain field in a specific table in the database. Tree view representation has various functions: first it provides designers with a visual hierarchical structure of data representing the components, items, and various features of products such as the function of each part, behaviour, and structural characteristics. Features are considered variables which have different values in each design case. Values of these variables are decided by designers in the design process and can provide constraints for the design problem under consideration. The second function is that it provides the incorporated creative tools with the structured design knowledge it requires to implement its methods for exploration of new design concepts.

Designers at the early stages of the design process can view and update data using the general data grid views. Further in the design process where more concepts are generated the tree view structure is used because it provides a wider scope of the design problem taking into consideration the various design details. Since visualization in the design process is considered very crucial and can hinder or enhance the creative design process, it

was recognized that a different view option is required other than the grid view of data used earlier. Figure 6.12 presents a snap shot of an early data update using the grid view control. On the other hand figure 6.13 presents a tree view of a sample design alternative in the concept mapping tool window showing every single detail of that sample.

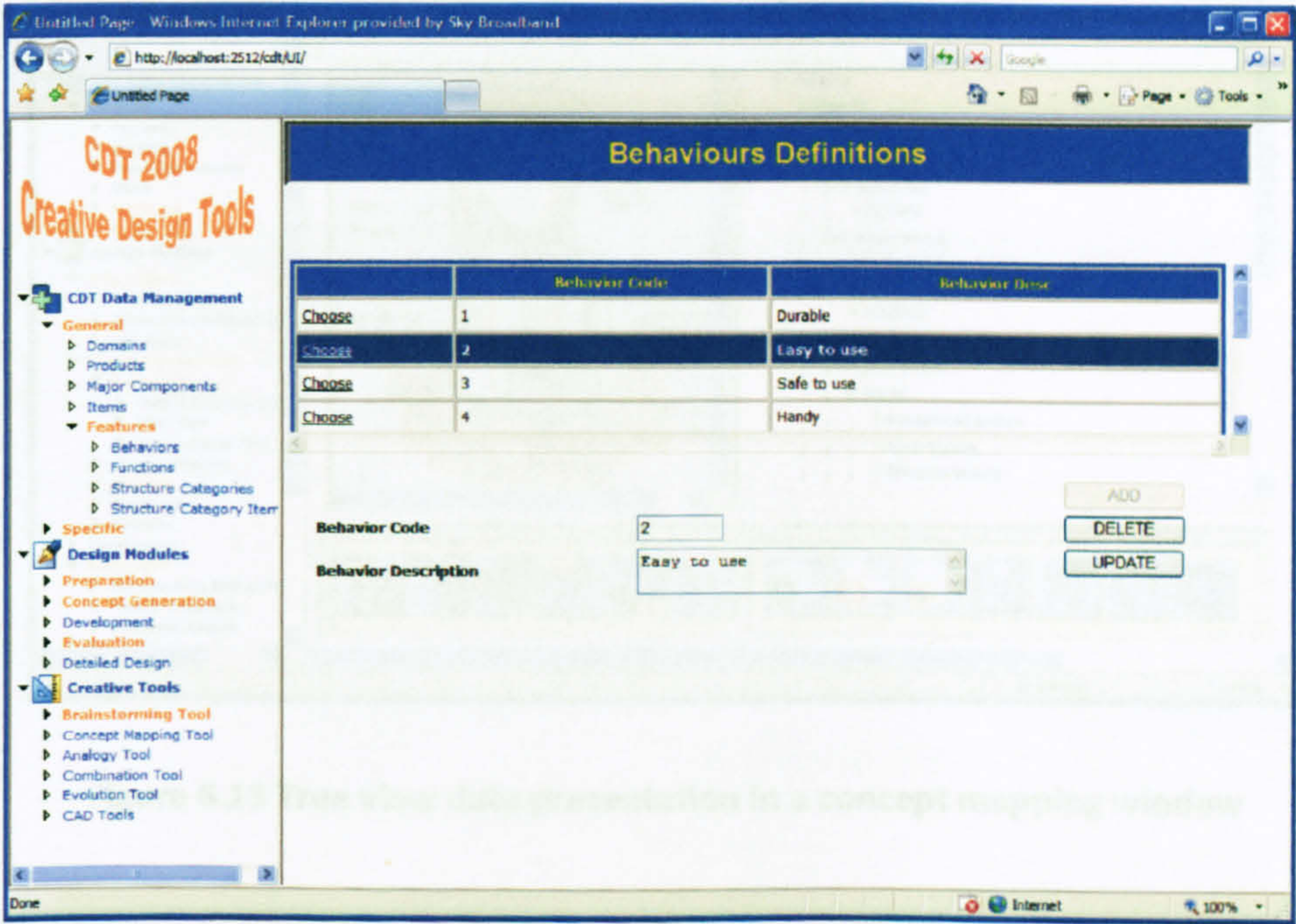


Figure 6.12 Example of a grid view data presentation

Data grid views provide a general scope of the data where all the data in the table is presented, while the tree view displays only one case at a time but with more related elements all displayed to give a comprehensive detailed view of that specific case. Therefore, the use of the grid view presentation is useful for updating the databases like adding new design knowledge related to the new problem situation. It provides a complete picture of the existing knowledge in the databases to identify the missing knowledge required for this problem situation. On the other hand when the problem is focused and

more details are added the tree view can be more useful to create a holistic view of that specific case.

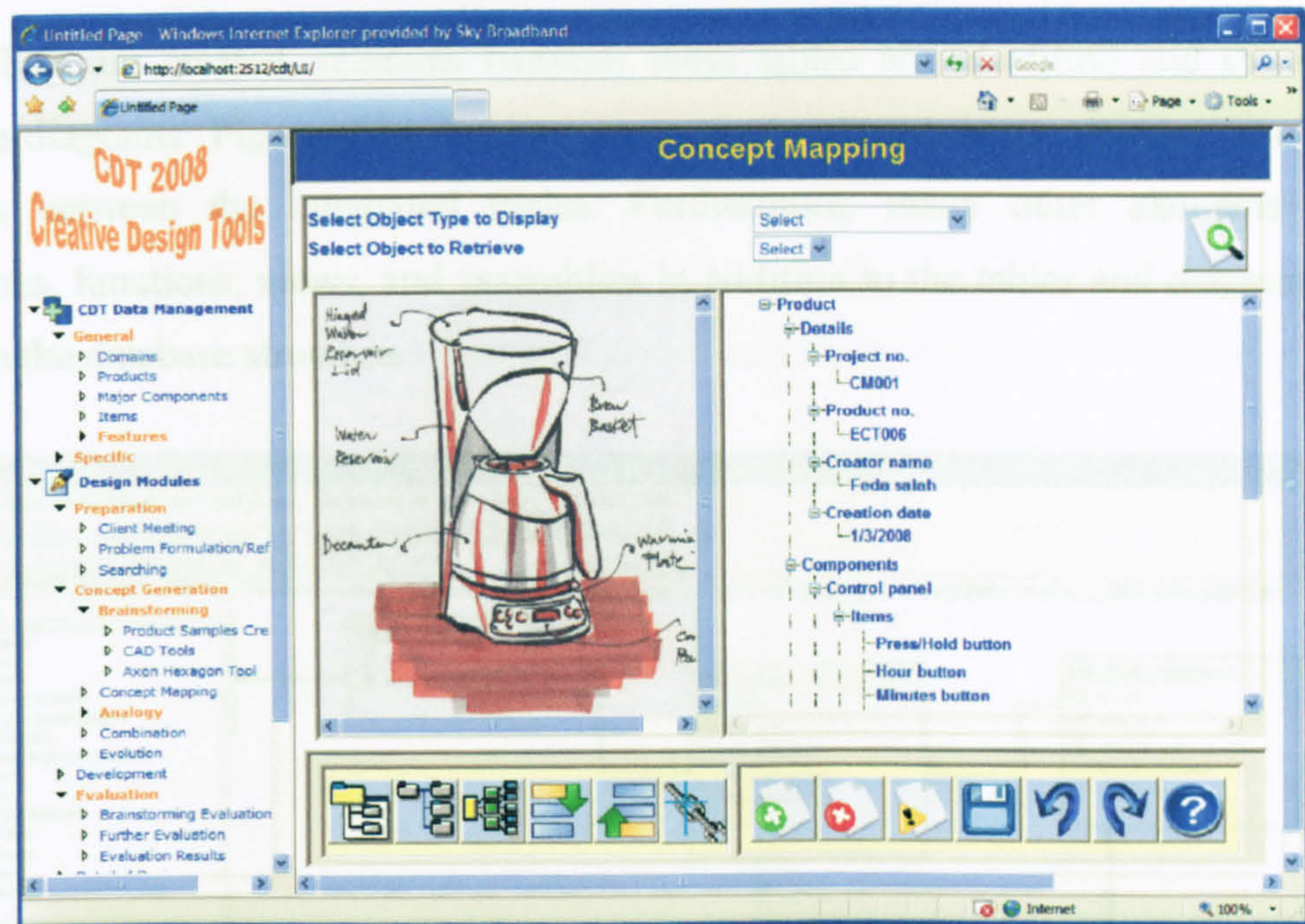


Figure 6.13 Tree view data presentation in a concept mapping window

6.6 Knowledge Databases and Display Implementation

Structured Query Language (SQL) server 2005 has been used to create the databases encompassed in the CDT system. SQL server stores data in the form of tables with columns and rows. The columns represent the fields while the rows represent the data records stored in the table. The columns are the variables and each of them has a name and a type.

The Microsoft Visual Studio 2005 provides users with the possibility to create databases from within Visual Studio interface. The database elements can be viewed and amended from the database explorer window while working on the system implementation. Furthermore the various data are stored in a folder within the solution explorer window

named (App_Data). This makes the retrieval and any amendment of the databases easier and faster.

After tables are created, relations between these tables are identified and stored in the database diagrams. Figure 6.14 displays an example of a database diagram showing the relations between the integrated tables. Furthermore, many other elements such as procedures, functions, views, and assemblies in addition to the tables and diagrams can be stored in the database structure.

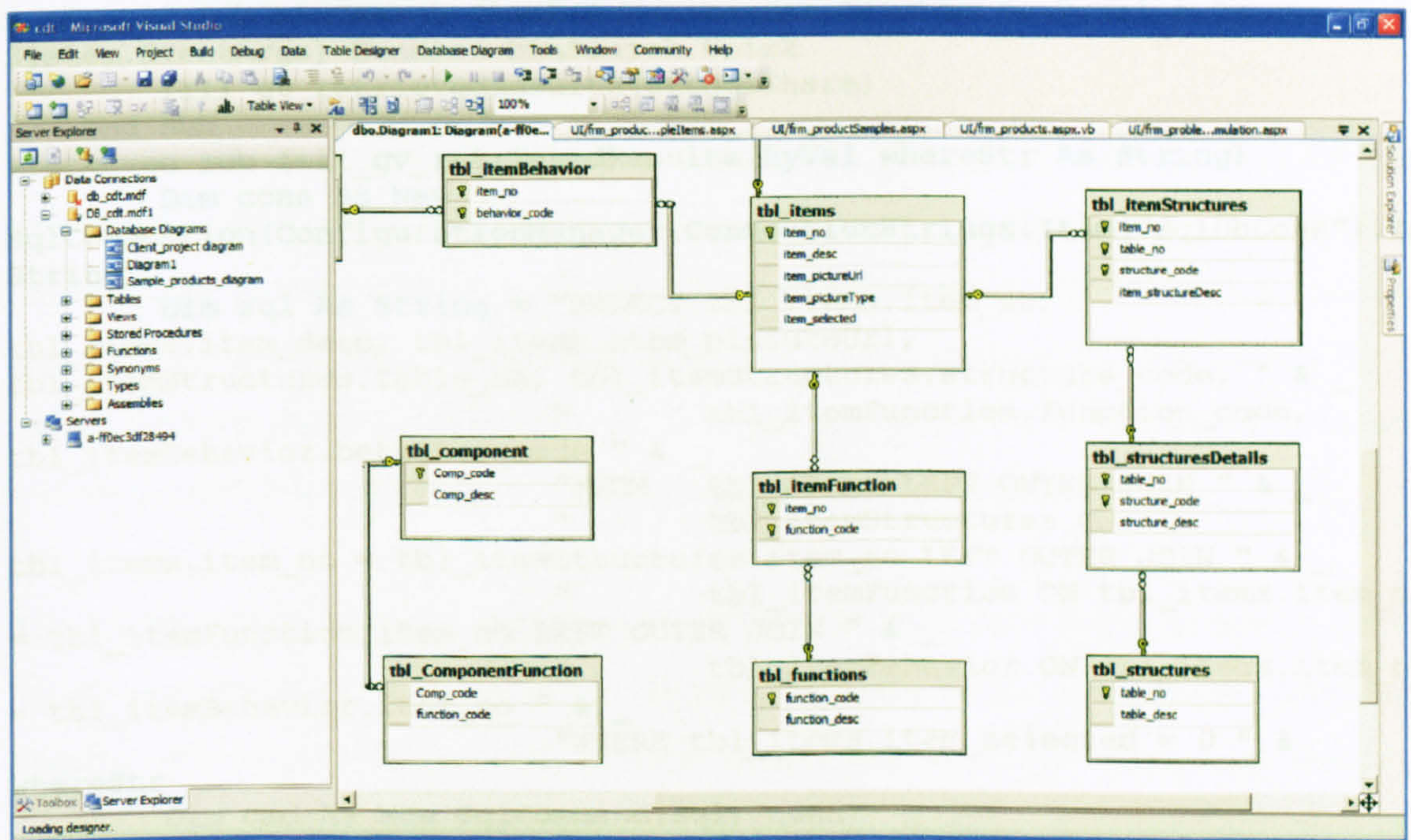


Figure 6.14 Example of a database diagram in the implemented CDT system

Retrieving data from web applications is achieved by using data source web controls. Various data sources can be accessed in the Visual Studio environment such as SQL, Access, Object, and Xml data sources. These data sources act as bridges between the ASP.NET pages and databases. These data source web controls only retrieve the data from the databases but do not display them. Other means for displaying the data are required.

Visual Studio has several data web controls namely: grid view, data list, details view, form view, and repeater.

In the CDT system data is accessed using SQL data source web controls. Each control of them is programmed to connect to a specific table or tables in the database, retrieve required specific fields, and display them in a specific data web control. Furthermore, queries can be identified and conditional constraints can be applied on the retrieved data. The following is an example of a data connection source code with search procedure:

```
Protected Sub btnSearch_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles btnSearch.Click
    fill_gv_retrievedResults(GetSqlWhere)
End Sub
Protected Sub fill_gv_retrievedResults(ByVal whereStr As String)
    Dim conn As New
SqlConnection(ConfigurationManager.ConnectionStrings.Item("SqlDbConn").To
String)
    Dim sql As String = "SELECT tbl_items.item_no,
tbl_items.item_desc, tbl_items.item_pictureUrl,
tbl_itemStructures.table_no, tbl_itemStructures.structure_code, " & _
        "tbl_itemFunction.function_code,
tbl_itemBehavior.behavior_code " & _
        "FROM tbl_items LEFT OUTER JOIN " & _
        "tbl_itemStructures ON
tbl_items.item_no = tbl_itemStructures.item_no LEFT OUTER JOIN " & _
        "tbl_itemFunction ON tbl_items.item_no
= tbl_itemFunction.item_no LEFT OUTER JOIN " & _
        "tbl_itemBehavior ON tbl_items.item_no
= tbl_itemBehavior.item_no " & _
        "WHERE tbl_items.item_selected = 0 " &
whereStr
    Dim cmd As New SqlCommand(sql, conn)
    conn.Open()
    Dim reader As SqlDataReader = cmd.ExecuteReader
    gv_retrievedResults.DataSource = reader
    gv_retrievedResults.DataBind()
    conn.Close()
    errlbl.Text = ""
End Sub
Protected Function GetSqlWhere() As String
    Dim sqlWhere As String = ""
    If ddl_behaviors.SelectedIndex <> 0 And ddl_behaviors.Items.Count
> 0 Then
        sqlWhere &= " and tbl_itemBehavior.behavior_code=" &
ddl_behaviors.SelectedValue
    End If
```



```

        If ddl_functions.SelectedIndex <> 0 And ddl_functions.Items.Count
> 0 Then
            sqlWhere &= " and tbl_itemFunction.function_code=" &
ddl_functions.SelectedValue
        End If
        If ddl_structureCategoryItems.SelectedIndex <> 0 And
ddl_structureCategoryItems.Items.Count > 0 Then
            sqlWhere &= " and tbl_itemStructures.structure_code=" &
ddl_structureCategoryItems.SelectedValue
        End If
        If ddl_structureCategoryItems.SelectedIndex <> 0 And
ddl_structureCategoryItems.Items.Count > 0 Then
            sqlWhere &= " and tbl_itemStructures.table_no=" &
ddl_structureCategoryItems.SelectedValue
        End If
        Return sqlWhere
    End Function

```

Knowledge database management in the developed CDT system took the form of multi web pages which are directly connected to the integrated databases. The knowledge identification focused activity is divided into two major stages. The first stage involves general and specific data management while the second involves the preparation for the design problem under consideration. Both stages are conducted by designers to identify knowledge which is relative to the design problem under consideration.

The general stage involves identification of new general knowledge necessary for the design problem space such as design domain, products, major components, items, and features such as general functions, behaviours, and structures. For example to identify a new structure's feature, a structure category needs to be identified, and then items are added to this new category. Figure 6.15 shows the structure category web form where new categories are identified such as style, size, colour, material and many more as required. The style category can have classical, modern, and high tech items' values. These items' values are flexible because they can vary for each design problem. That is the reason behind the CDT system providing the designers with this flexibility in creating their own knowledge to suite their requirements and their design problems. This same method applies to all other data management web forms.

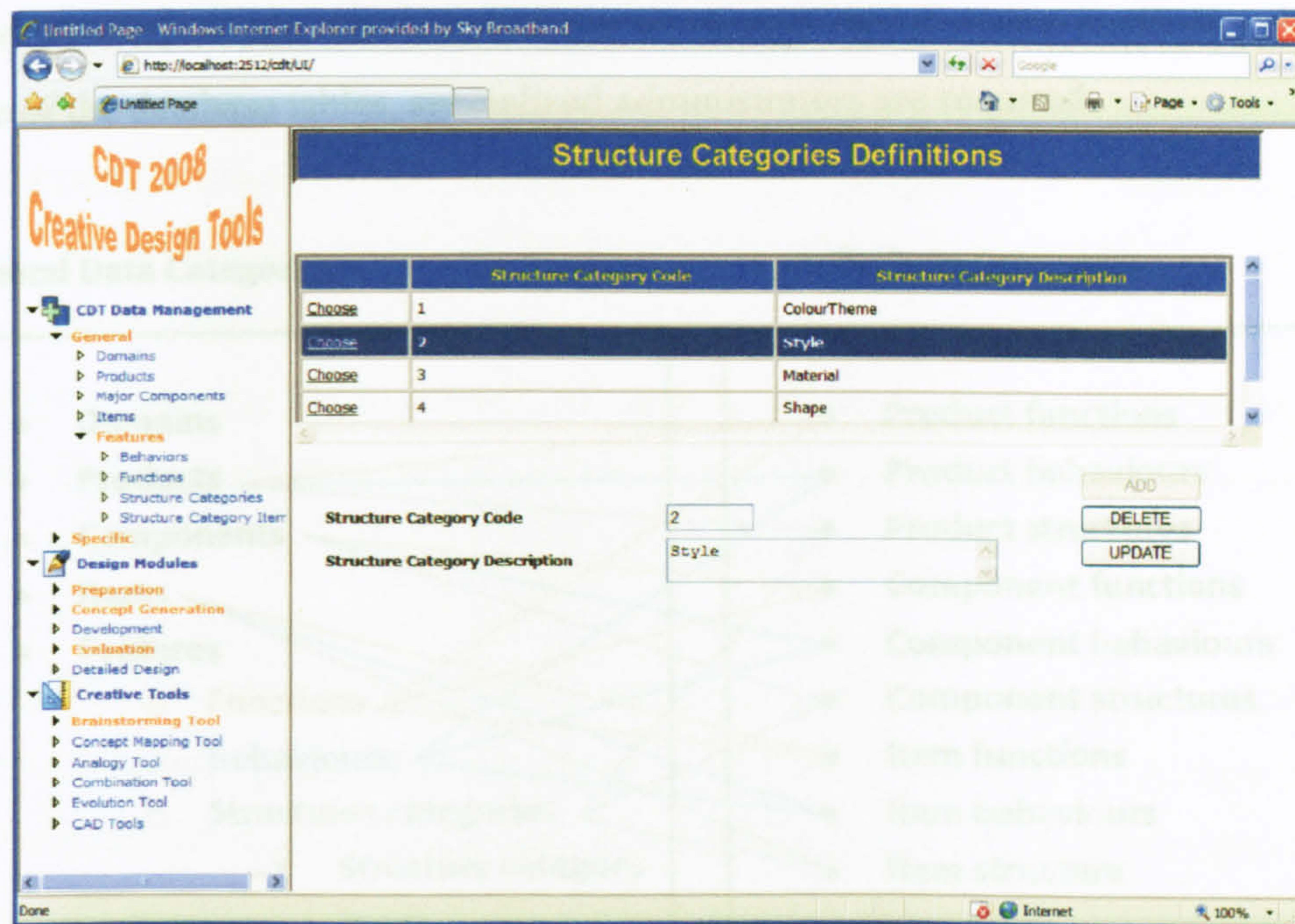


Figure 6.15 Structure categories definitions form showing the grid view

The specific stage involves the identification of specific features related to specific products, components, and items. These specific features are usually selected from the general data stored in the first stage and attached to each identified product, component and item as shown in figure 6.16. For example the product of a coffee maker can have a style feature value which is modern. This value of the style feature is selected from the drop down list control which displays the data previously identified in the structure category items web form.

The designer's input is collected by using text box and drop down list controls. The data inserted, updated, or deleted can be displayed immediately in the GridView web control. The GridView web control displays the data of databases' tables. The use of web display controls provides an easy way to monitor the design knowledge through the CDT system interface. This also manages the degree of control provided for the users over the databases.

They are allowed to edit the data but not to change the structure itself. To change the structure of the database tables, specialized administrators are required.

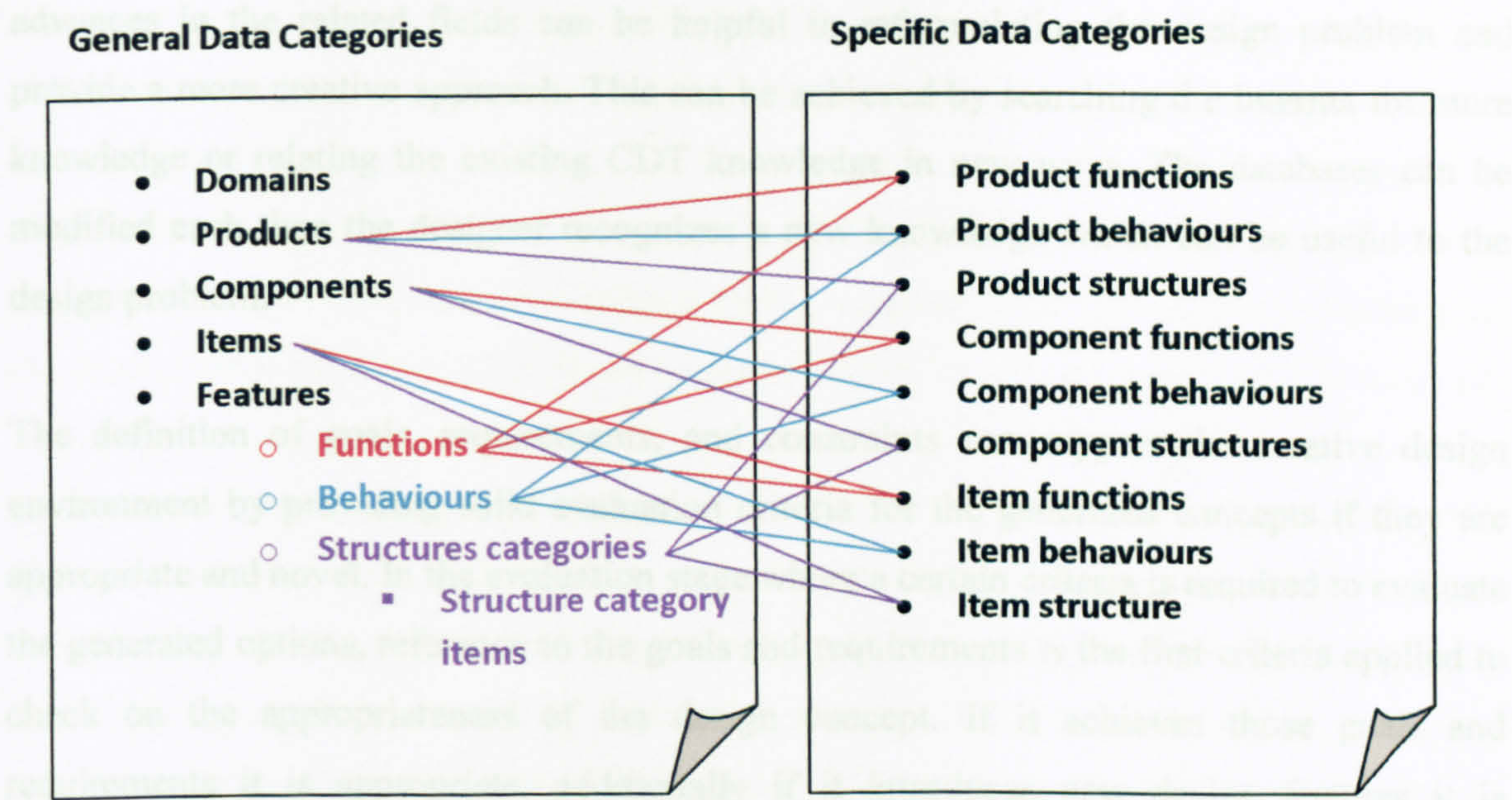


Figure 6.16 Relation between general data and specific data categories

In the product samples web form, designers are given the choice to store images of the design samples in the database. The designer can browse the images stored in the system or in his/her own computer and upload the image and store it as the sample image in that specific sample raw. The image type is flexible; therefore, several image types can be retrieved and stored. This flexibility is achieved by storing the image Uniform Resource Locator (URL) and the image type in the database table as separate fields.

The preparation stage is more problem oriented, for it involves the identification of more specific design knowledge relative to the design problem situation. The identified knowledge is stored in the system to support the achievement of a creative design solution. This knowledge is usually obtained from meetings with clients to define the design problem goals, requirements, and boundaries and from searches conducted by the designers. The

search tool can help in achieving a wider scope of the problem by reviewing related knowledge regarding the design problem. Some previous solutions achieved by other designers make a good example. Moreover, new technologies, new materials and any new advances in the related fields can be helpful in reformulating the design problem and provide a more creative approach. This can be achieved by searching the internet for more knowledge or relating the existing CDT knowledge in new ways. The databases can be modified each time the designer recognizes a new knowledge which can be useful to the design problem.

The definition of goals, requirements, and constraints can support the creative design environment by providing solid evaluation criteria for the generated concepts if they are appropriate and novel. In the evaluation stage where a certain criteria is required to evaluate the generated options, reference to the goals and requirements is the first criteria applied to check on the appropriateness of the design concept. If it achieves those goals and requirements it is appropriate, additionally if it introduces new design features it is considered creative. A design concept which has been evaluated as novel but not appropriate is not considered a successful creative idea.

6.7 *Creative Tools Implementation*

Each incorporated tool has one or more web form user interfaces as a way of communication with the designer to enhance his/her thinking through the application of its methods either to generate or explore new design concepts. Each tool has a unique implementation scheme, although they all share the same design knowledge representation format. Various data web controls have been used to display design knowledge in the different tools such as GridView, DetailsView, and TreeView controls. Drop down list controls have also been used to display the options available for the designer to choose from. Furthermore, ordinary text buttons, and image buttons have been provided to implement certain functionalities. In the following paragraphs a detailed explanation of the implementation schemes of the incorporated tools is illustrated.

The incorporated creative tools have been implemented to utilize the developed design representation discussed in CHAPTER FIVE. The features identified at the early stages of data management can be used to apply constraints on the solution design space. A certain value for the function constraint can retrieve certain alternatives from the database with that specific function. If the search is for a component which function is heating, then alternatives which have this function are retrieved. Therefore, this limits the design solution space according to the constraints applied by the designer. This approach of implementing the constraints tactic is very flexible and constraints can be relaxed or tightened as required.

The brainstorming tool has been implemented based on the design computational approach discussed in CHAPTER FIVE as three related methods; brainwriting, brainsketching, and brainrelating. The main aim of brainstorming is to put ideas on display. In the brainstorming session window a multi text box has been used to gather designers' description of the idea; furthermore, an image control has been incorporated to display the designer's sketch or image of the created concept. More text boxes have been included to enter the product ID, project ID, and creator ID. All created concept details are stored in the brainstorming table for retrieval by other designers to view, evaluate, and select the most appropriate concepts to continue the design process. Several image buttons have been included with various functions which can be useful for the brainstorming tool. In the Axon2008 tool window, hexagon diagrams can be created with the different parts related to each other which is stored as well and can be retrieved for further considerations. Another brainstorming window has been designed to create new samples from existing components and items existing in the CDT database. Various items can be retrieved using the features of behaviour, function, and structure as the constraints for the search process. Interesting items are selected and added to the sample table, when all the items are complete the sample is created and displayed with its all components. This tool can help the designer in creating design alternatives from existing ones if not creating his/her own from scratch. Figure 6.17 shows sample creation activity illustrating search procedure.

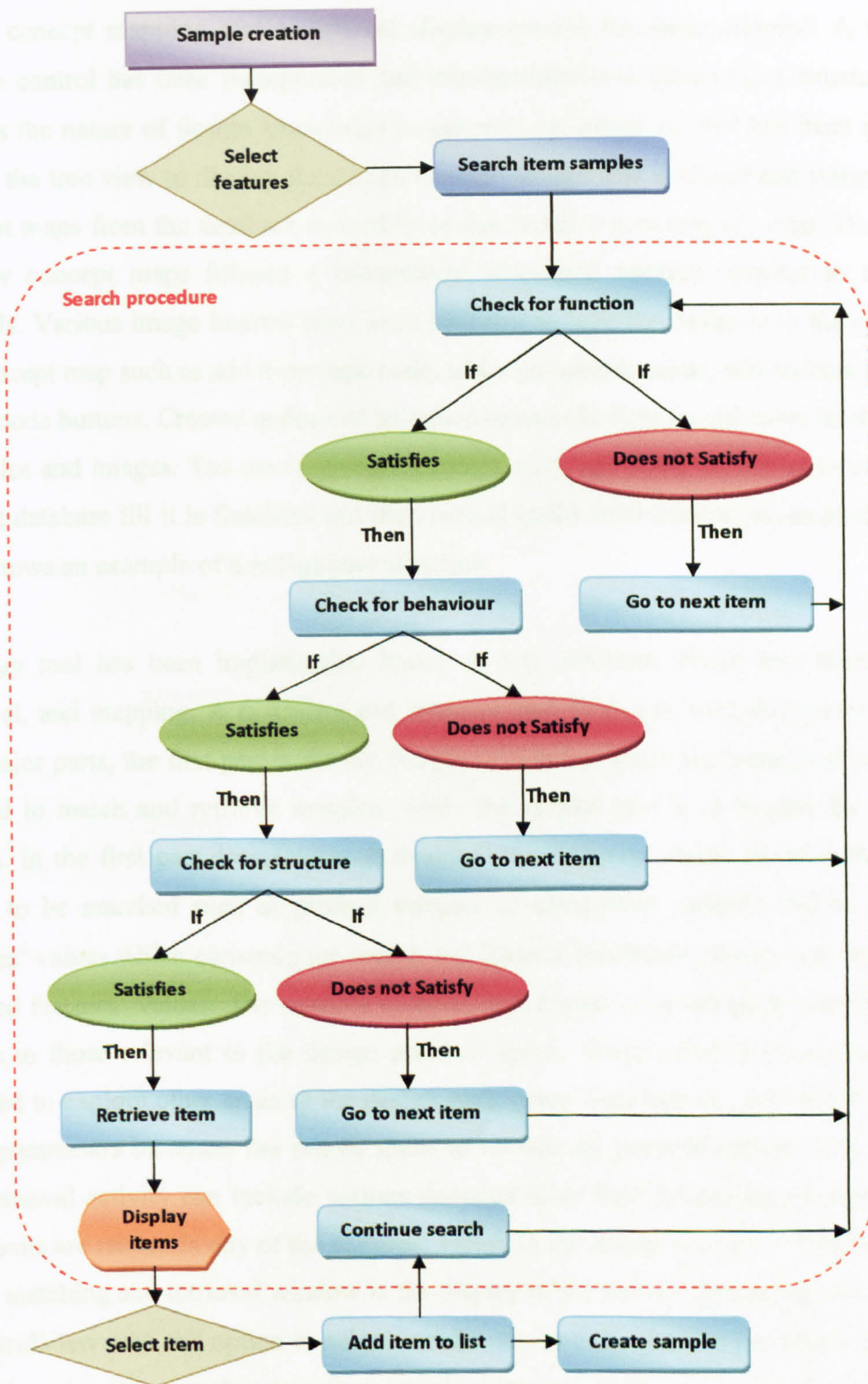


Figure 6.17 Sample creation search procedure

In the concept mapping tool a different display control has been adopted. A tree view display control has been incorporated and implemented in a hierarchical structure which reflects the nature of design knowledge in general. An image control has been integrated beside the tree view to display the design concept image. The designer can retrieve stored concept maps from the database to modify or can create a new concept map. The creation of new concept maps follows a hierarchical structured method relevant to tree view controls. Various image buttons have been included to help the designer in the creation of the concept map such as add a concept node, add a component node, add an item node, and link a node buttons. Created nodes can be linked to specific files to add more details such as data files and images. The newly created concept maps are stored in the temporary active project database till it is finalized and then moved to the final destination database. Figure 6.18 shows an example of a refrigerator structure.

Analogy tool has been implemented based on two activities which are: matching and retrieval, and mapping. A matching and retrieval web form has been designed to include two major parts, the first part is for the designer's input to select the analogical parameters applied to match and retrieve samples, while the second part is to display the retrieved results. In the first part designers need to select the category which specifies the type of tables to be searched such as product samples or component samples and to select the features' values which constrain the search and focus it on certain objects that satisfy these selected features' values. The selected category and features' values help in restricting the results to those relevant to the design problem space. These selected parameters can be changed to explore other areas of the design state space. Furthermore, non-selecting any of these parameters increases the search space to include all possible options. The matching and retrieval activity can include various domains other than the design problem but still the results are related in any of the features' values to the design problem. The second part of the matching and retrieval window is the display of the results. The results are displayed in a GridView with the option to select certain results to be used in the mapping activity. The selected options are then transferred to the mapping web form where other methods are applied. Figure 6.19 shows the analogy matching and retrieval procedure.

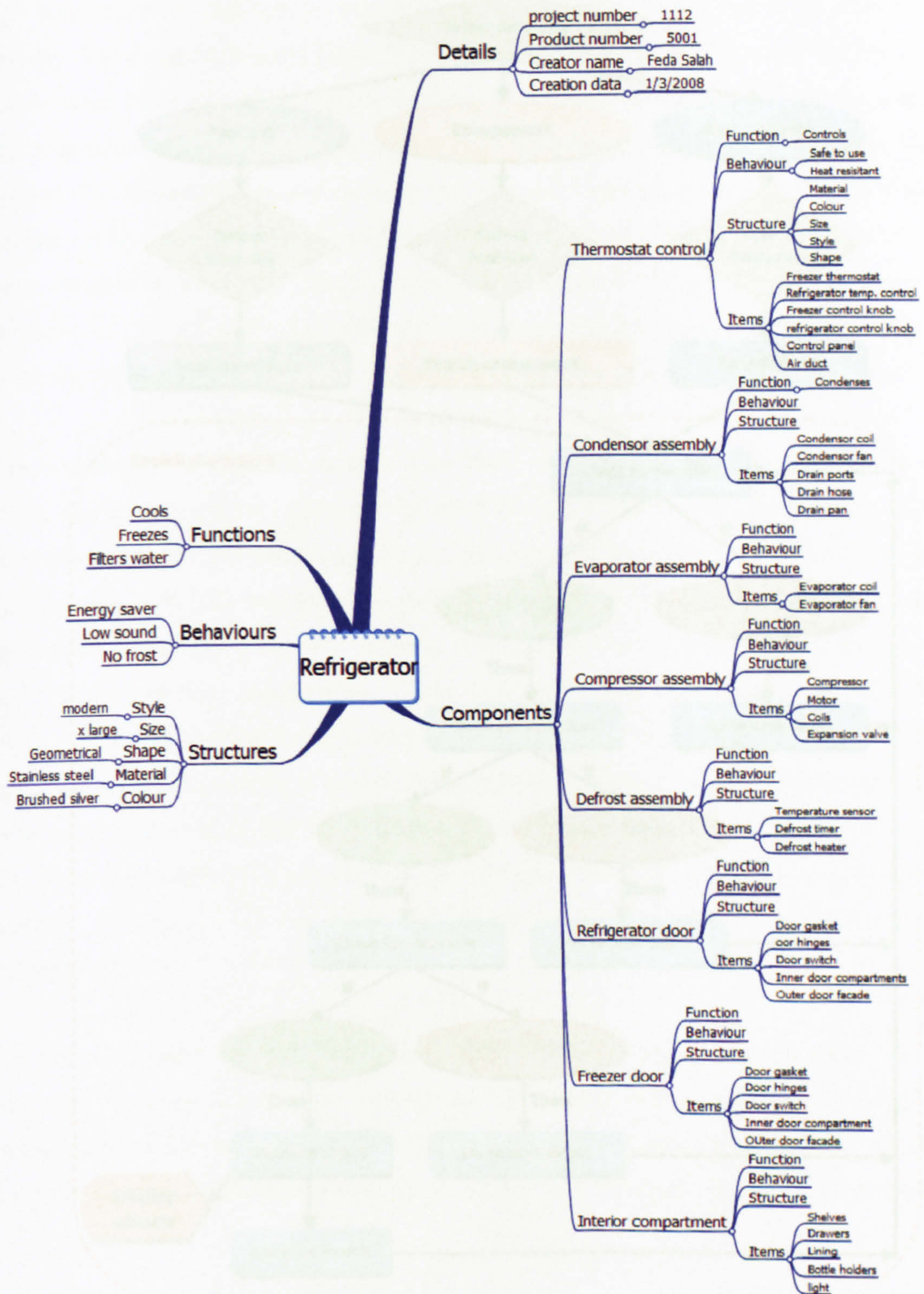


Figure 6.18 Example refrigerator structure diagram

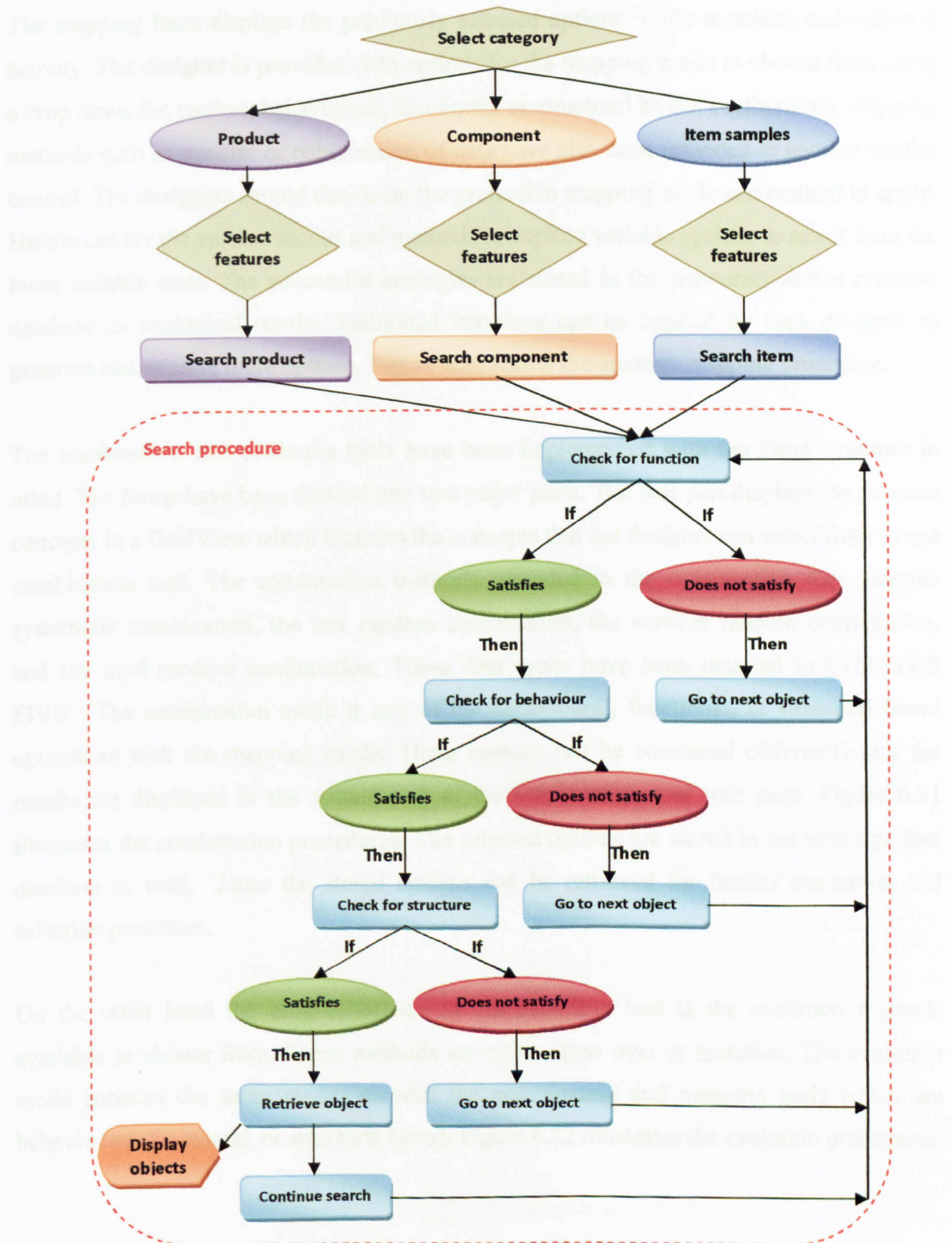


Figure 6.19 Analogy matching and retrieval procedure

The mapping form displays the previously selected options in the matching and retrieval activity. The designer is provided with options for the mapping mode to choose from using a drop down list control; behavioural, functional, or structural based. Furthermore, mapping methods such as transfer or combination of data have also been provided in another similar control. The designers should decide on the preferable mapping mode and method to apply. He/she can try the various modes and methods to explore variable options to select from the more suitable ones. The successful analogies are stored in the temporary active problem database as analogical results. Unlimited iterations can be applied by each designer to generate and explore more options. Figure 6.20 shows the analogy mapping procedure.

The combination and evolution tools have been implemented with the same structure in mind. The forms have been divided into two major parts. The first part displays the selected concepts in a GridView which includes the concepts that the designer can select from to use combination tool. The combination methods provided in the combination form are the systematic combination, the tree random combination, the vertices random combination, and the total random combination. These four types have been detailed in CHAPTER FIVE. The combination mode is any of the behavioural, functional, or structural based options as with the mapping mode. These options can be combined differently and the results are displayed in the second part of the combination tool web page. Figure 6.21 illustrates the combination procedures. The selected options are stored in the active project database as well. Later the stored options can be retrieved for further evaluation and selection processes.

On the other hand the only difference in the evolution tool is the evolution methods available to choose from. These methods are either cross over or mutation. The evolution mode contains the same modes as with the combination and mapping tools which are behavioural, functional, or structural based. Figure 6.22 illustrates the evolution procedures.

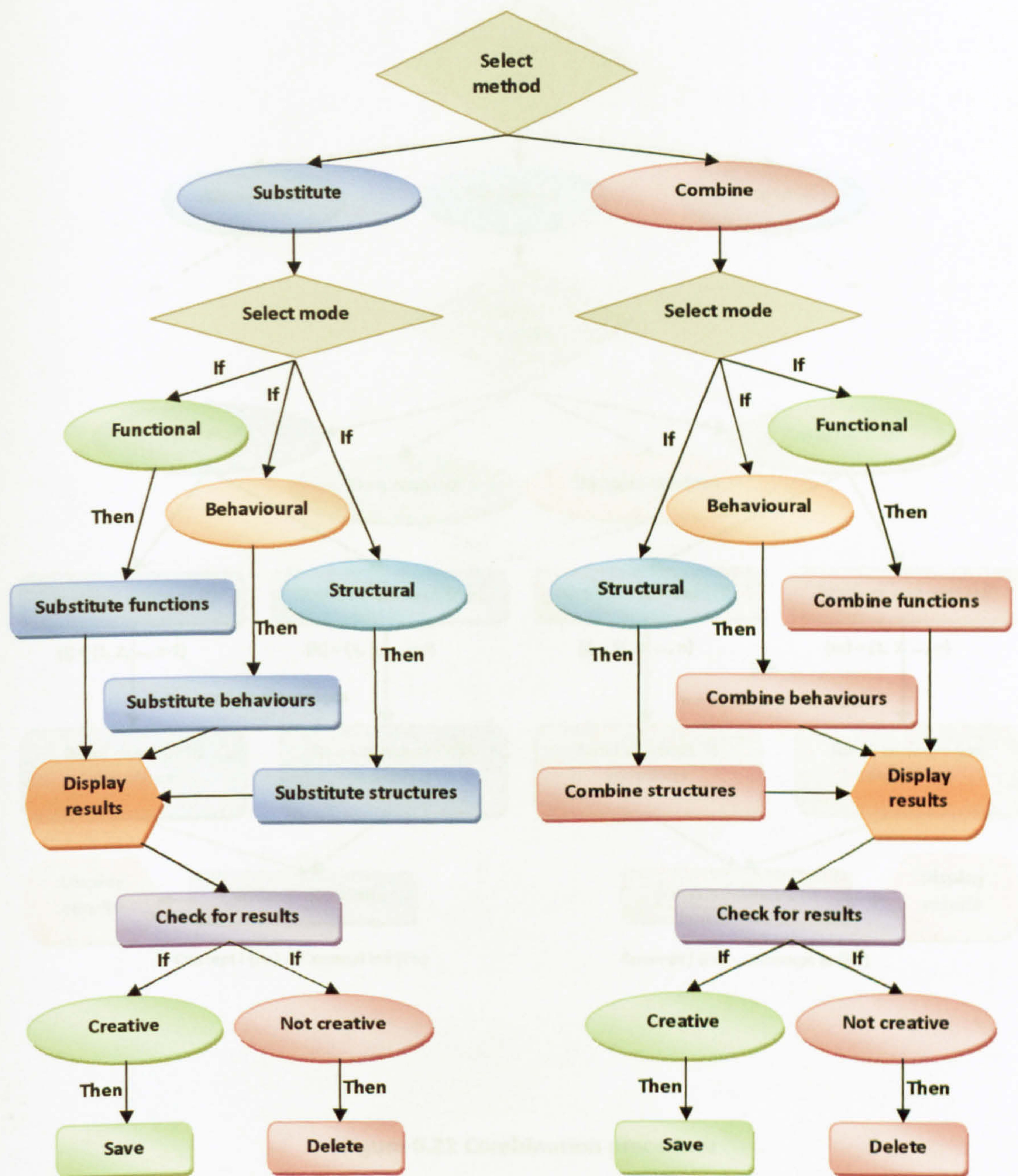


Figure 6.20 Analogy mapping procedure

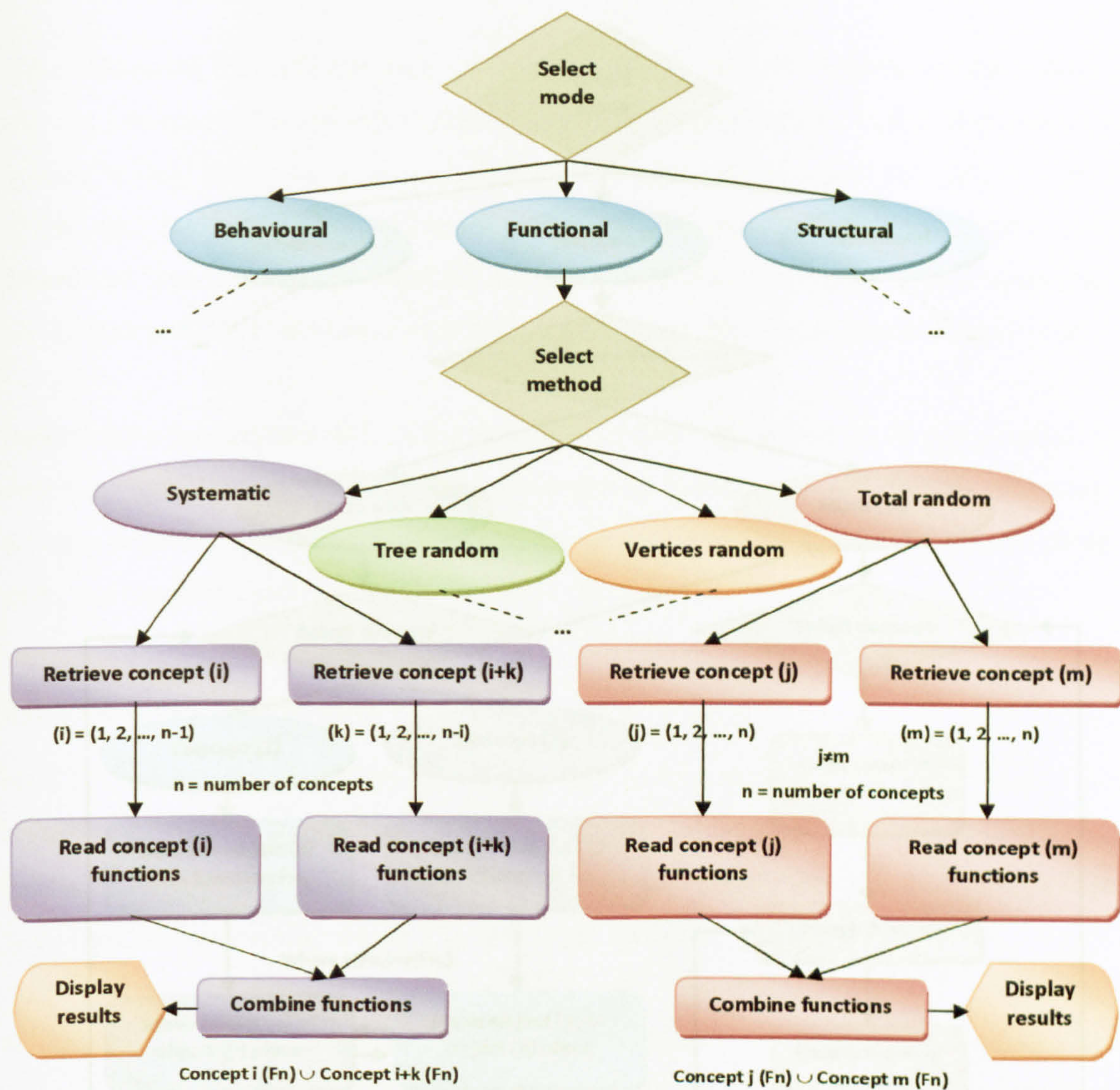


Figure 6.21 Combination procedure

6.2 Design Consistency

After discussing the CDT system's architecture, the design representation, the databases, and the implementation of the various design consistency algorithms, the CDT system, several important factors must be considered. The design consistency of the CDT system are worth to be developed. The design consistency of the CDT system are worth to be developed and used by the designers. This requires the design consistency of the CDT system.

Furthermore, the user interface of the CDT system should provide a consistent design, principles all over the whole system. The design consistency of the CDT system is necessary to create a desirable design. The design consistency of the CDT system is necessary to create a desirable design.

6.2.1 Informal Design

New design consistency algorithms are being developed. The design consistency of the CDT system is necessary to create a desirable design. The design consistency of the CDT system is necessary to create a desirable design.

to all users should be consistent. The design consistency of the CDT system is necessary to create a desirable design. The design consistency of the CDT system is necessary to create a desirable design.

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various design consistency algorithms are being developed. The design consistency of the CDT system is necessary to create a desirable design. The design consistency of the CDT system is necessary to create a desirable design.

designers with an efficient design consistency algorithm to design a consistent design. The design consistency of the CDT system is necessary to create a desirable design. The design consistency of the CDT system is necessary to create a desirable design.

functions were improved. The design consistency of the CDT system is necessary to create a desirable design. The design consistency of the CDT system is necessary to create a desirable design.

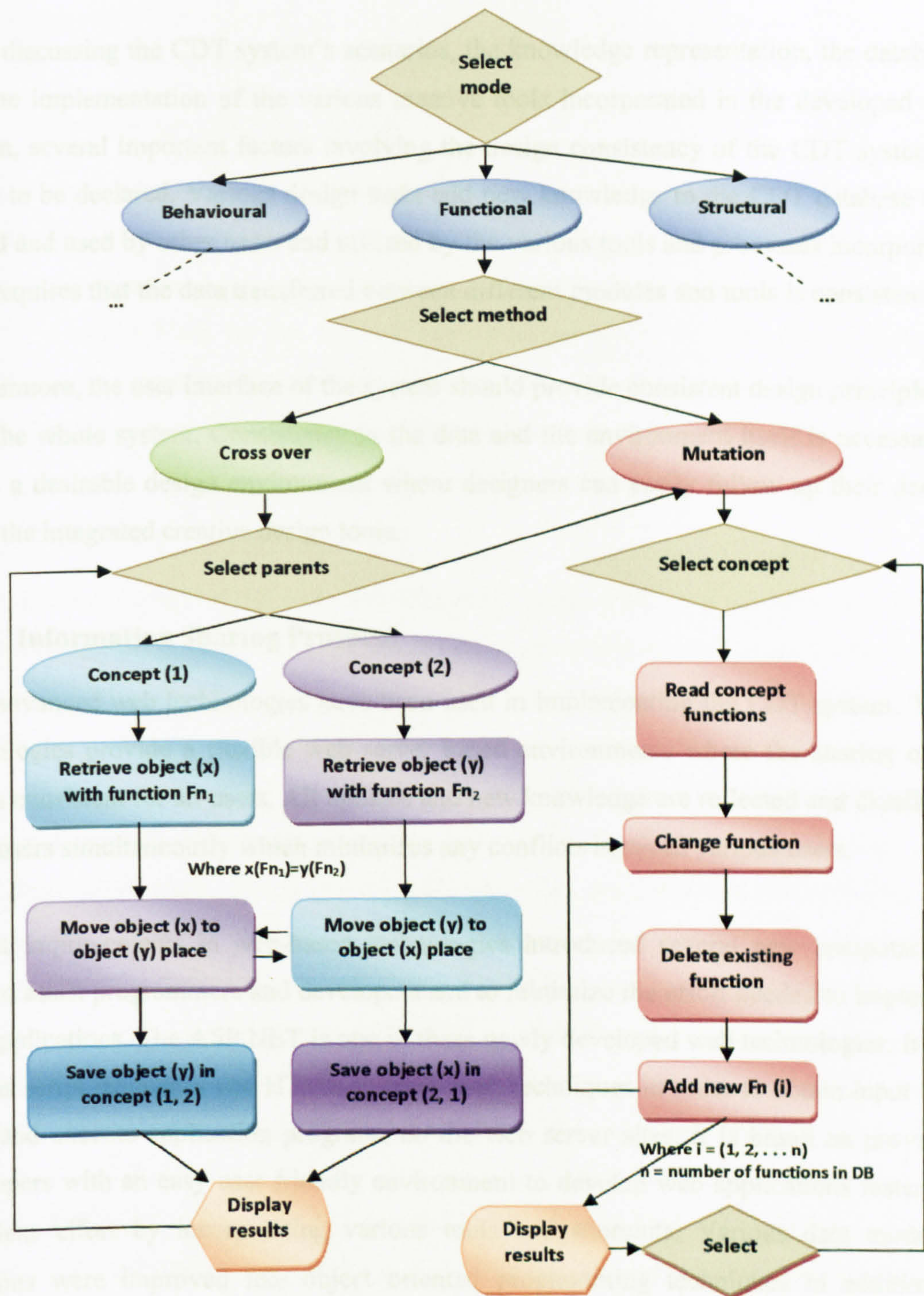


Figure 6.22 Evolution procedure

6.8 Design Consistency

After discussing the CDT system's scenarios, the knowledge representation, the databases, and the implementation of the various creative tools incorporated in the developed CDT system, several important factors involving the design consistency of the CDT system are worth to be declared. Various design tasks add new knowledge to the CDT database to be shared and used by other users and utilized by the various tools and processes incorporated. This requires that the data transferred between different modules and tools is consistent.

Furthermore, the user interface of the system should provide consistent design principles all over the whole system. Consistency in the data and the environment itself is necessary to create a desirable design environment where designers can easily follow up their designs using the integrated creative design tools.

6.8.1 Information Sharing Protocol

New advanced web technologies have been used in implementing the CDT system. These technologies provide a flexible web server based environments where the sharing of the data is consistent for all users. All updates and new knowledge are reflected and distributed to all users simultaneously which minimizes any conflicts between various users.

Recent improvements in web-based technologies introduced several new computational tools to assist programmers and developers and to minimize the effort needed to implement web applications. The ASP.NET is one of these newly developed web technologies. It uses various script languages and HTML to apply web techniques in order to obtain input from users and execute application programs on the web server sites. It is based on providing developers with an easy user friendly environment to develop web applications faster and with less effort by incorporating various tools and shortcuts. Various data modeling functions were improved like object oriented programming techniques in addition to relational data structures, eXtensible Markup Language (XML) to organize information in a hierarchical structure which can be extracted and displayed using web browsers. And many

more advances which are beyond this research scope that can be dealt with as open future research activities.

6.8.2 Data Sharing and Structuring

Shared design systems require effective, standardized data structuring and sharing between the different teams. This has been achieved by the developed design knowledge representation discussed earlier. The structuring and sharing of data can facilitate the use of the CDT creative tools by the various designers and teams in different locations. Its flexibility acts as a neutral design language structure among different design cultures. It can be modified as situations change between various design environments.

6.8.3 Conflict Resolution

Creative thinking starts at the very early stages of design which can inhibit a high level of subjective conflicts. This is usually at the design stages where detailed variables are still not determined. Defining certain requirements at the beginning in regard to the functionality, behaviour, and structure of the design problem can act as constraints for the design creation specifically at the early stages of preparation and concept generation. The CDT system as explained earlier provides the flexibility for designers to identify the design problem space at the preparation stage. When the designer identifies the functional requirements of a certain product, these requirements will be used to retrieve any required related data within this requirement boundary. These new data identified by designers should have a specific data type to be saved in the database. The CDT system identifies the conflict between the data identified by the designer and the data source format. Afterwards the system notifies the user by displaying conflict messages with possible solution alternatives.

The Visual Studio.NET technology provides various user input validation controls for conflict resolution which made this issue a breeze compared to previous technologies. Examples of such controls are the RequiredFieldValidator, the CompareValidator, the RangeValidator, and the RegularExpressionValidator. Data inputs can be divided into two

types, required and optional. The RequiredFieldValidator control ensures that the user enters a value for the required particular input; therefore null values are not acceptable, whereas in the optional data input the user has the choice of not providing the data. The CompareValidator control is used to make sure that the data type entered is the same as required, for example for numeric inputs, the data entered should be a number not a string. This data type validation ensures that the text entered by the user can be converted to the data type the computer expects. Furthermore, it can compare if the values entered by the users are less than, less than or equal, equal, greater than, greater than or equal, or not equal to some stored value or to another user value. On the other hand, the RangeValidator ensures that a certain input value is within a range of two constant values. This control is very useful when identifying constrained numeric details in the design process according to some design features. The RegularExpressionValidator is useful when certain types of string input must match a certain format such as phone numbers or address post codes. This makes the search easier for the computer when certain format is stored in the database.

In the CDT system several types of validation controls have been used, they all share the category of communicating with the user regarding some errors in the data entering types, formats or if the data is required or not. A uniform user interface has been applied all over the web pages of the CDT system. The error message is usually displayed at the top under the title of the web page with red colour to draw the attention of the user to read it and to act based on its displayed message.

6.9 Summary

The CDT prototype system has been described in detail in this chapter. The developed system incorporates and combines various creative tools to enhance designers thinking from a holistic point of view through the different various design processes. Several features have been enclosed in a user friendly flexible environment to provide a holistic approach in creative design thinking. It has been shown how the implementation of the CDT system using the latest advanced web technologies supported the main aim of

achieving a holistic flexible approach. Several aspects have been discussed in this chapter starting with the CDT system scenarios, web technology used, the design knowledge representation developed, the databases implemented, the tools incorporated, and the design consistency of the developed system. The CDT prototype system contained various features to achieve the main aim described in section 1.3, these features are summarized below:

- The developed system incorporated creative tools for the whole design process with more emphasis on the early design stages of preparation and concept generation where most of the creative thinking is conducted.
- The implementation of a general hierarchical design knowledge representation in a flexible and abstract manner which can be worked upon by designers, other users, and creative tools which has been displayed using several display controls such as TreeView and GridView.
- The use of highly advanced web technologies in the development of the CDT prototype system which provided several advantages over old technologies such as ease of use, shorter implementation time, and more efficient environment with minimum implementation efforts in programming and maintenance.
- The developed system ensured design consistency between various modules and tools. Conflicts have been minimized when transferring data between different tools or between modules. This has been achieved by the integration of the various validation controls which minimized the required effort in conflict resolution programming.
- The situatedness in design is achieved by the flexibility in formulating the design problem knowledge according to each designer's situation, culture, and vision.

Consequently the CDT system combined the mentioned features and integrated them in a holistic, user-friendly, and creative design environment to enhance creative design thinking which is considered a new contribution in the creative design research.

CHAPTER SEVEN

VALIDATION OF THE PROPOSED CDT SYSTEM

7.1 Overview

The purpose of this chapter is to validate and demonstrate the application of the developed techniques and tools of the CDT system and how it achieved its detailed aims and objectives. This application of techniques and tools demonstrates the representation of design data from the very early stages of design, to the use of incorporated creative tools to generate concepts, and ends with the evaluation of the generated concepts. This chapter brings together many of the techniques and tools of creative design thinking, discussed in the previous chapters, into a real example. It displays how designers can use and explore creative design alternatives through the effective implementation of the developed integrated system.

7.2 Introduction

The developed system enables designers to explore more design alternatives through their design process, by providing support from the initial stages of design throughout the more detailed ones. The system provides designers with creative techniques and tools within a flexible environment which is adaptable to any given design problem. Various examples of design stages have been chosen to demonstrate the case study. This was to illustrate the system's capabilities for identifying the design knowledge, formulating/reformulating the design problem, generating creative conceptual alternatives, exploring more alternatives using various incorporated creative tools, and evaluating the generated concepts to develop the most creative ones.

Products from the kitchen appliances' sector have been chosen to validate the developed system. The initial level of concept generation of a refrigerator is demonstrated. However,

due to the complexity of this product, it is not practical to display the entire product details. Therefore, a specific design task of creating a new refrigerator product which encompasses new features at the conceptual stage has been chosen to demonstrate the capabilities of the incorporated tools to generate and explore new concepts. The detailed design processes of the product represented in this study were from the initial stages of design data identification to concept generation, exploration, and evaluation. The displayed stages of the design problem case study were:

- Product data management and sharing
- Design preparation
- Concept generation and exploration
- Design evaluation

These processes are the important steps in the early creation of any new product design and development. These processes are incorporated within the developed system and are integrated with creative tools to facilitate its functions. As a result the developed system provides a creative design environment which is flexible and facilitates collaboration among design teams.

7.3 Validation Objectives

The field of creative design thinking comprises a wide range of various tools and techniques. This validation concerns the techniques and tools of the developed system; to what extent they can be used to enhance creative thinking among designers, minimize design fixation, collaborate, and evaluate design alternatives.

The objectives of the validation are to:

- Use the CDT interface to assist designers in identifying new design knowledge, updating, and deleting any irrelevant data, in addition to support generation of creative design concepts and evaluation.
- Assure that data is shared by all design members and that all changes are reflected to all designers at the same time.
- Confirm that the developed design representation can facilitate the use of the incorporated creative tools as well as the designers' understanding of the design problem.
- Demonstrate the capabilities of the creative tools in retrieving or exploring new alternatives based on the data provided by designers to be evaluated and developed to the detailed design stages.
- Validate that the interface was capable of representing visual tools and integrating them in a flexible design environment.
- Explore how visualization of design knowledge and alternatives can enhance the creative design thinking by providing new scopes or directions which were not clear to designers earlier.
- Verify the assistance of the evaluation stages of individual, team, and society in revealing the most creative generated concepts.

7.4 Case Study Context

The primary intention of this research project has been the holistic approach to integrate various creative thinking tools, knowledge, and design processes to facilitate the creative design thinking among design teams. It focuses on the concept generation and evaluation of design alternatives. The case study is set in the domain of kitchen appliances for the purpose of demonstrating the system's capability in supporting creative design thinking.

The case study starts with the initial design data management and sharing of basic design information which formulates the base for the preparation stage where the problem is

formulated and more specific requirements and constraints are identified. Afterwards, through the use of various incorporated creative tools, design alternatives are generated and explored. Evaluation is conducted to validate and select the most creative ideas for development. The creation of new features (functions, behaviours, and structures) for the refrigerator has been chosen for representation. The refrigerator product has been explored in the case study and a hierarchical structure has been represented and used by the incorporated tools of the developed system.

7.5 Stage 1: Design Data Management and Information Sharing

The stage of design data management is to identify the basic knowledge required for the design problem under consideration. It is divided into two main parts namely general and specific. This stage demonstrates the flexibility of the developed CDT system by being adaptable to any design problem in any design discipline. The designers identify the required data and information according to the problem they want to solve. Therefore, the databases are updated with new data each time a new problem arises.

7.5.1 General Data Management

The data identified in this part is general data which can be used to define the specific data in the second part. It includes the design domains, products, components, items, and features such as behaviours, functions, structure categories, and structure category items.

Product design problems can belong to different domains such as electronics, furniture, mechanical, kitchen appliances and many others. Each design domain includes many specific products. Kitchen appliances for example includes, refrigerators, freezers, ovens, hobs, washing machines, tumble driers, dish washers and many other small appliances such as coffee makers or toasters. The first step in the general data management is the identification of the design problem domain. The case study's domain has been added to

the database as kitchen appliances. The case study domain definition's window, showing the various domains included in the system is illustrated in figure 7.1.

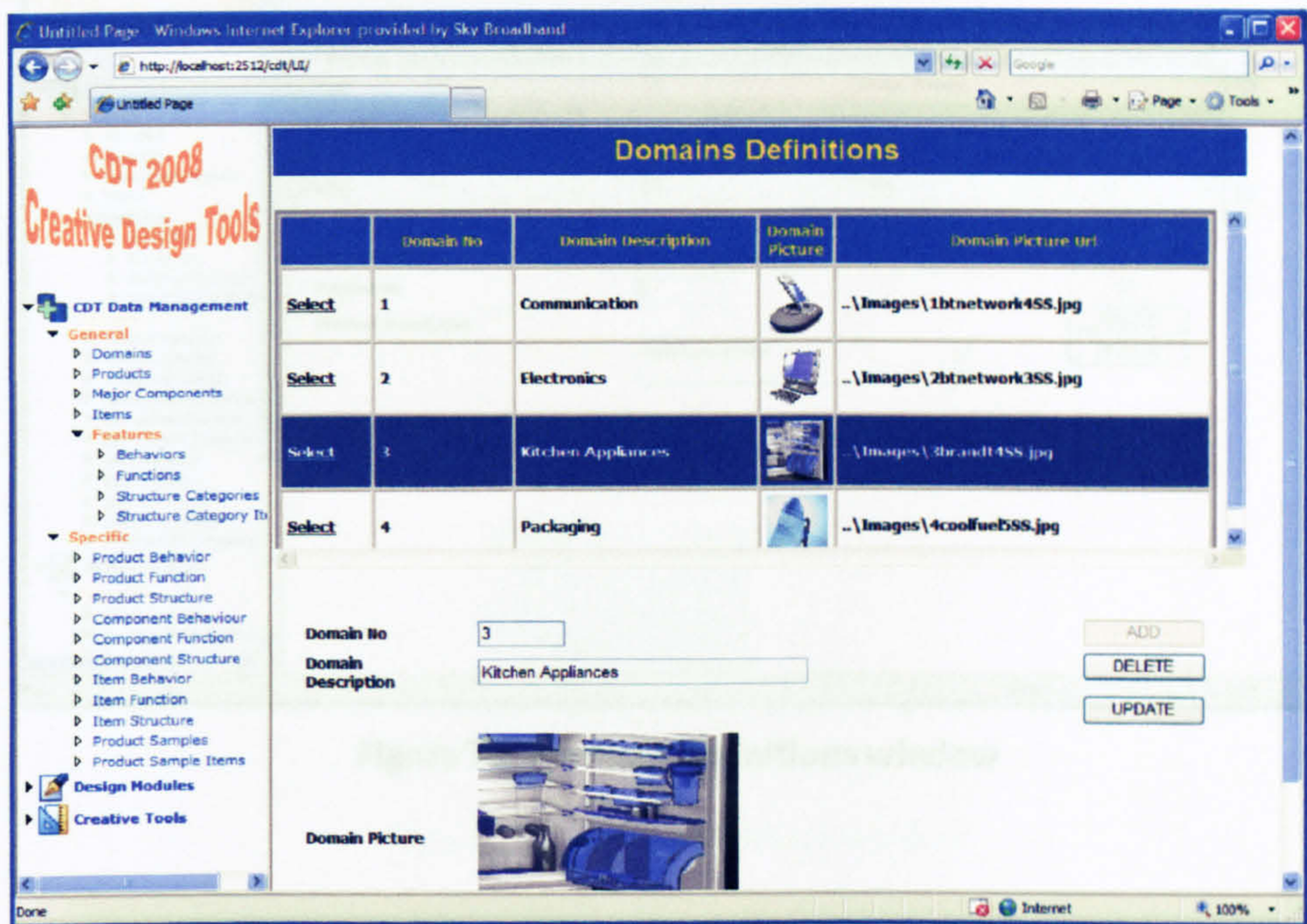


Figure 7.1 Domains definitions window

The identification of the product to be designed constitutes the next step. The identified product is attached to the relative domain defined earlier. Furthermore, basic common components and items are also defined and attached with that specific product. This provides a basis for all design team members to refer to when such data is required. The products, components, and items definitions windows are illustrated in figures (7.2 – 7.4) respectively.



Figure 7.3 Component definitions window

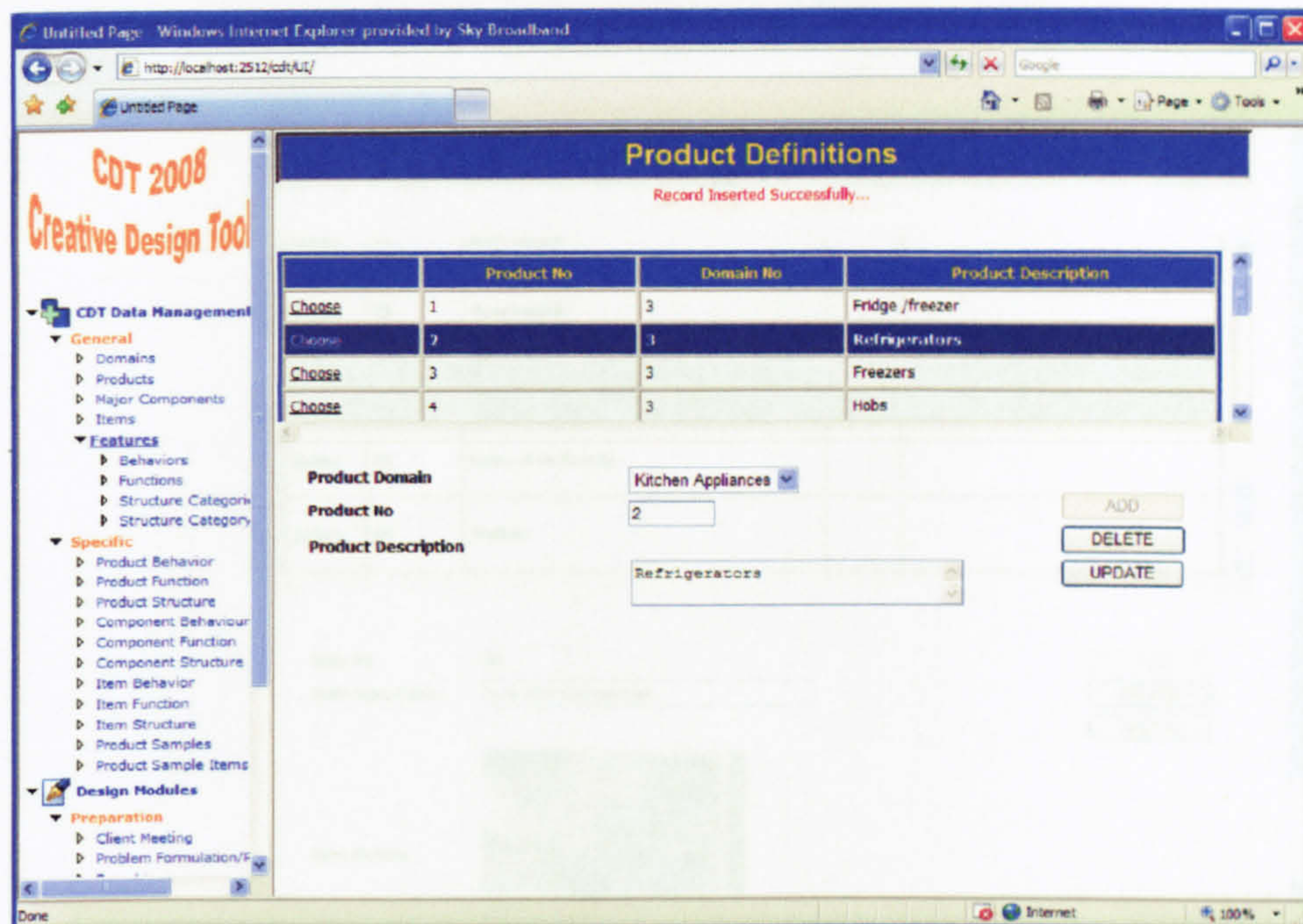


Figure 7.2 Products definitions window

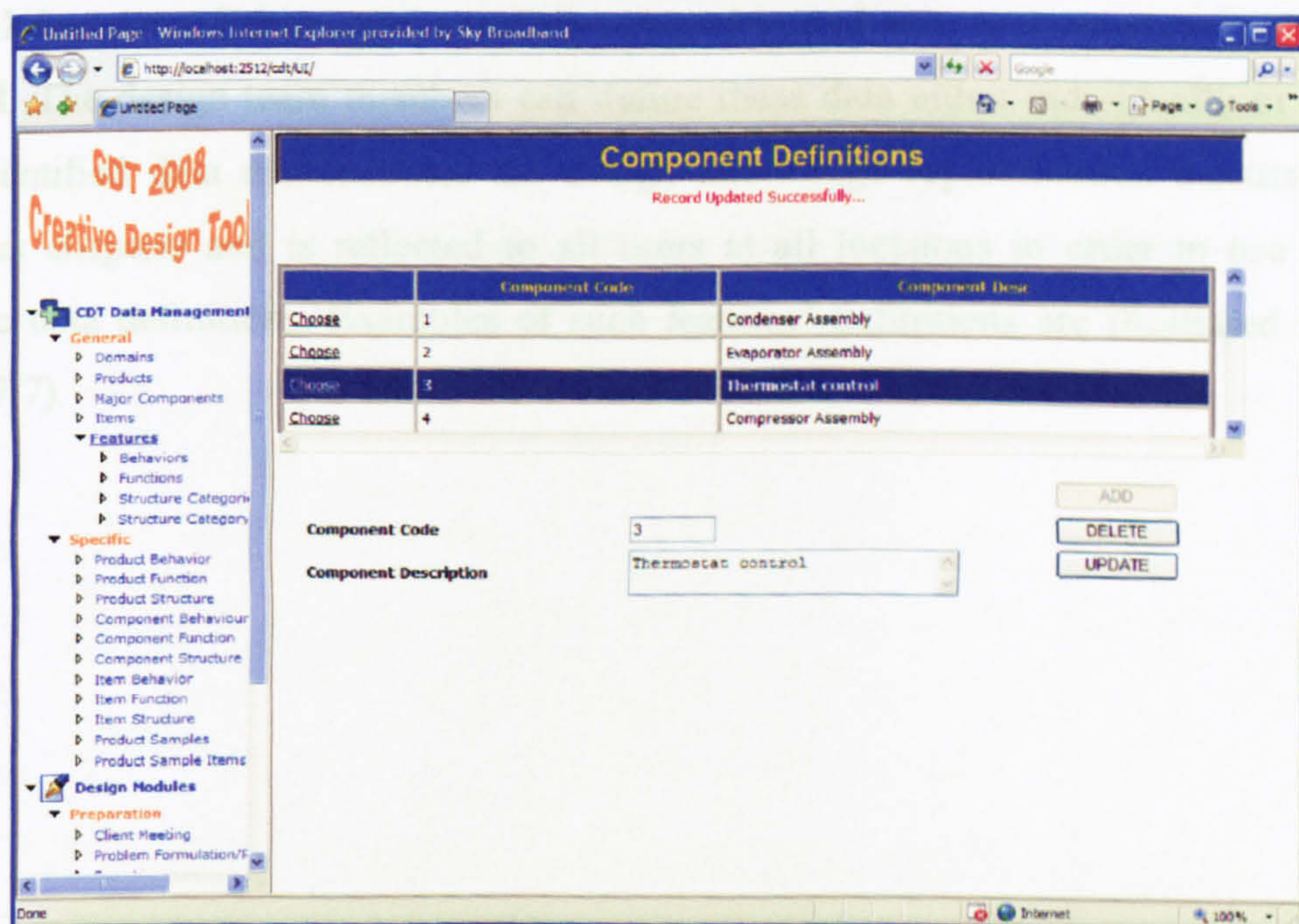


Figure 7.3 Component definitions window

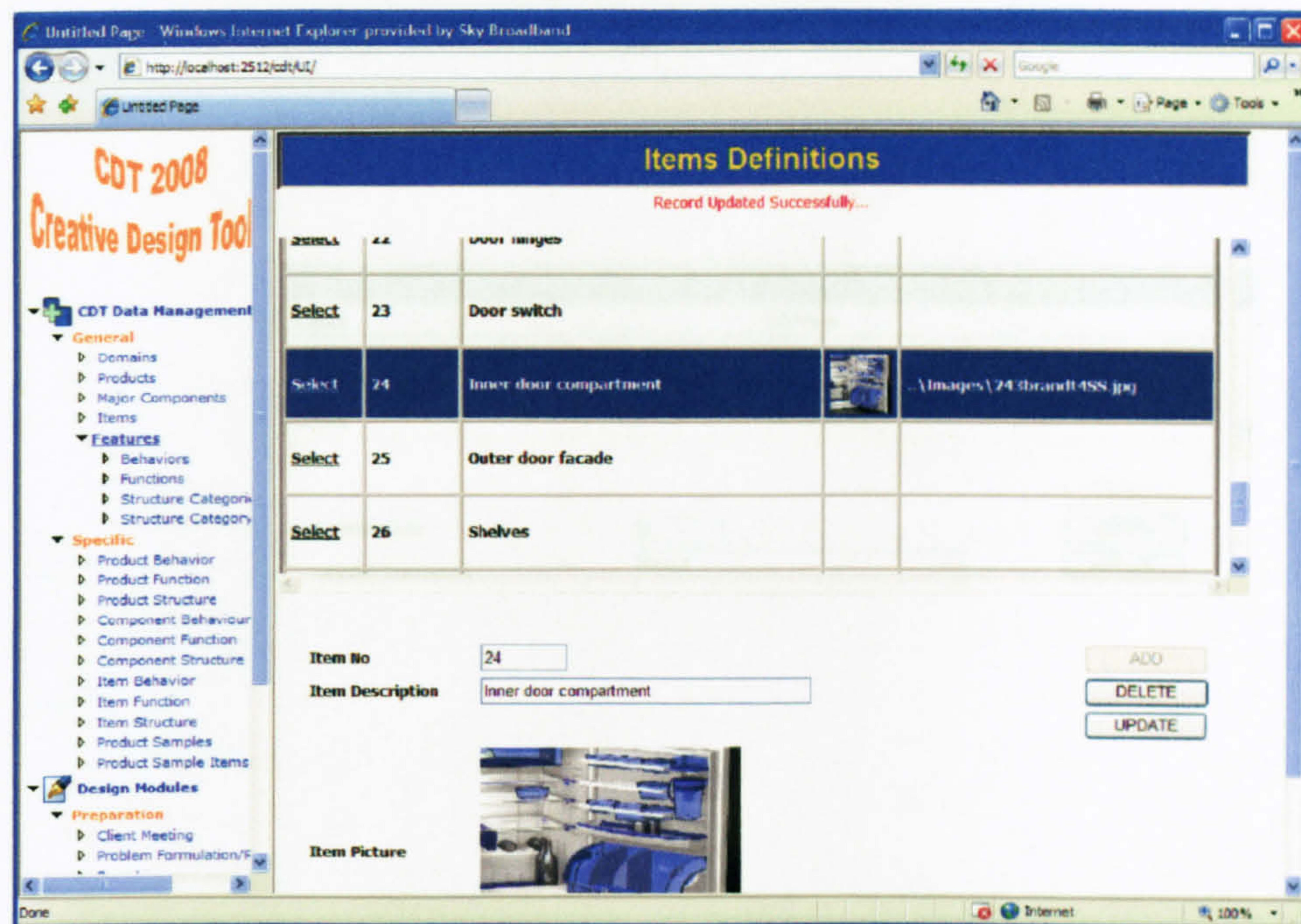


Figure 7.4 Items definitions window

General functions, behaviours, structure categories, and structure category items are also defined. The design team members can define these data either individually or as teams. The identified data demonstrates the design knowledge representation discussed in the previous chapters and is reflected to all users at all locations in order to use it for the specific data definitions. Examples of such features' definitions are illustrated in figures (7.5 – 7.7).



Figure 7.5 Behaviors definitions window

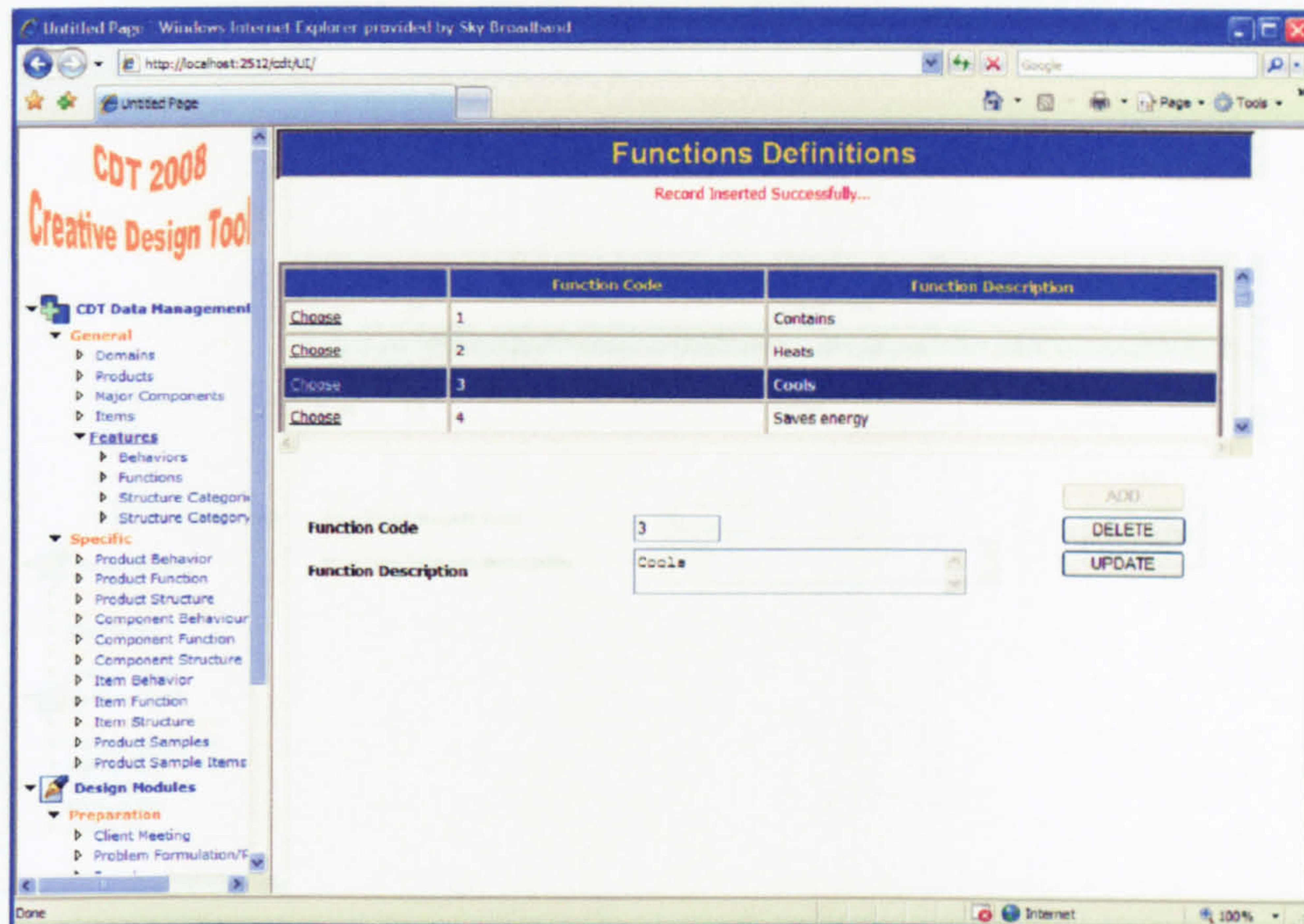


Figure 7.5 Functions definitions window

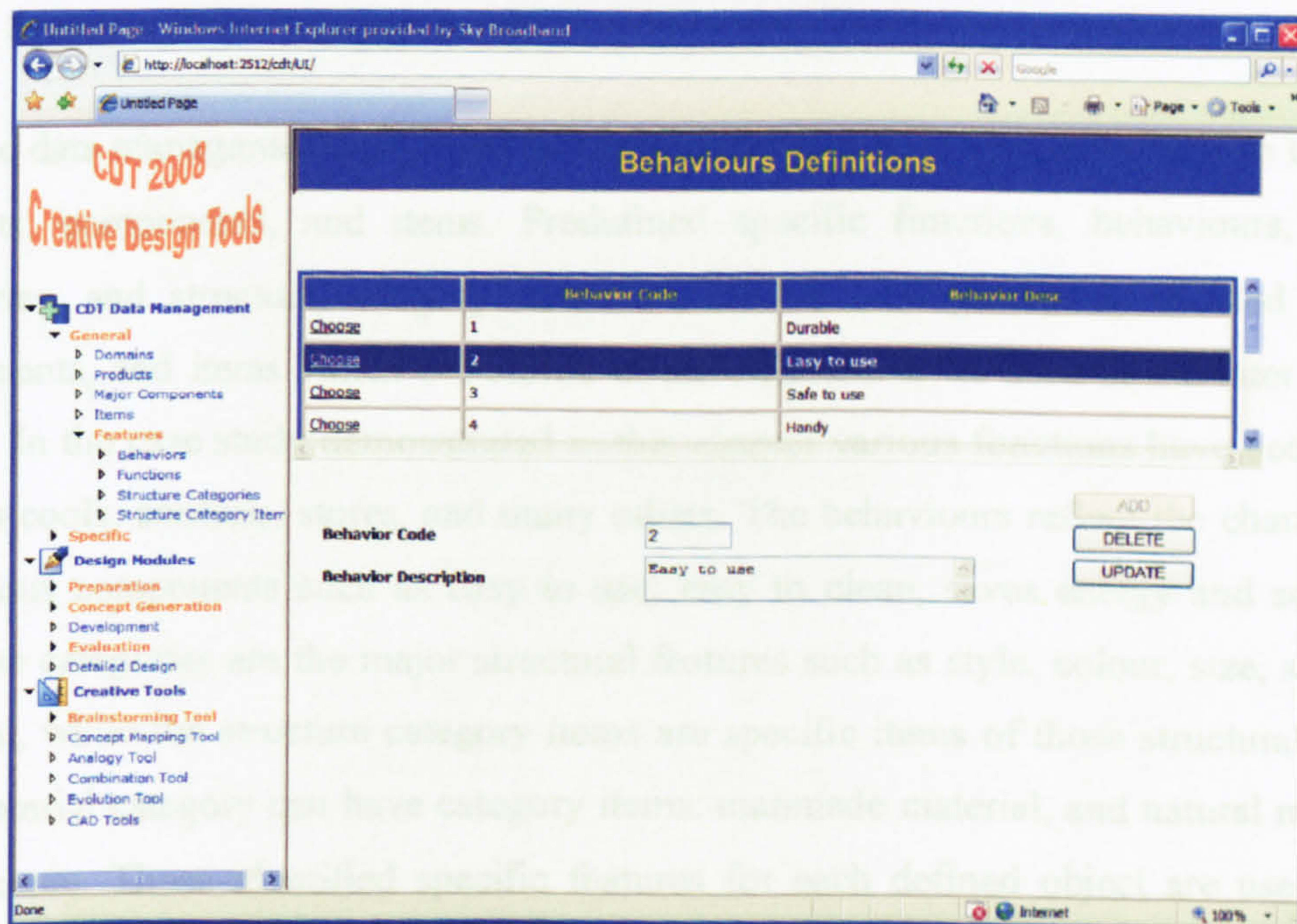


Figure 7.6 Behaviours definitions window

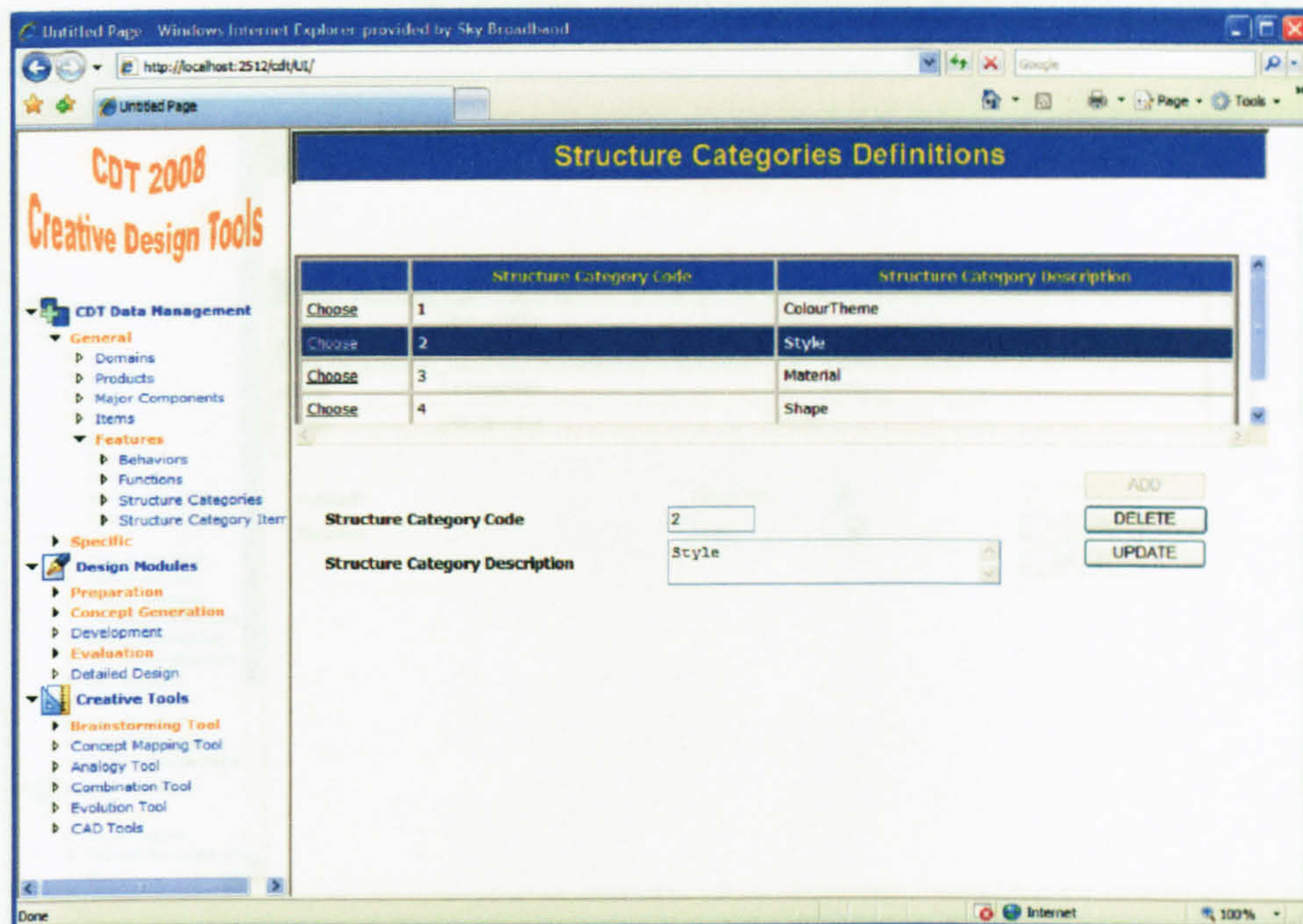


Figure 7.7 Structure categories definitions window

7.5.2 Specific Data Management

Specific data management is concerned with integrating the proper features with the related products, components, and items. Predefined specific functions, behaviours, structure categories, and structure category items are related with previously defined products, components, and items which are stored in the database to be used at the later stages of design. In the case study demonstrated in this chapter various functions have been defined such as cools, controls, stores, and many others. The behaviours reflect the characteristics of various components such as easy to use, easy to clean, saves energy and so on. The structure categories are the major structural features such as style, colour, size, shape, and material, while the structure category items are specific items of those structural features. The material category can have category items: manmade material, and natural material as an example. Those identified specific features for each defined object are used later as constraints in the developed system to retrieve objects with specific features. Some of the specific data management's windows are illustrated in figures (7.8 – 7.10).

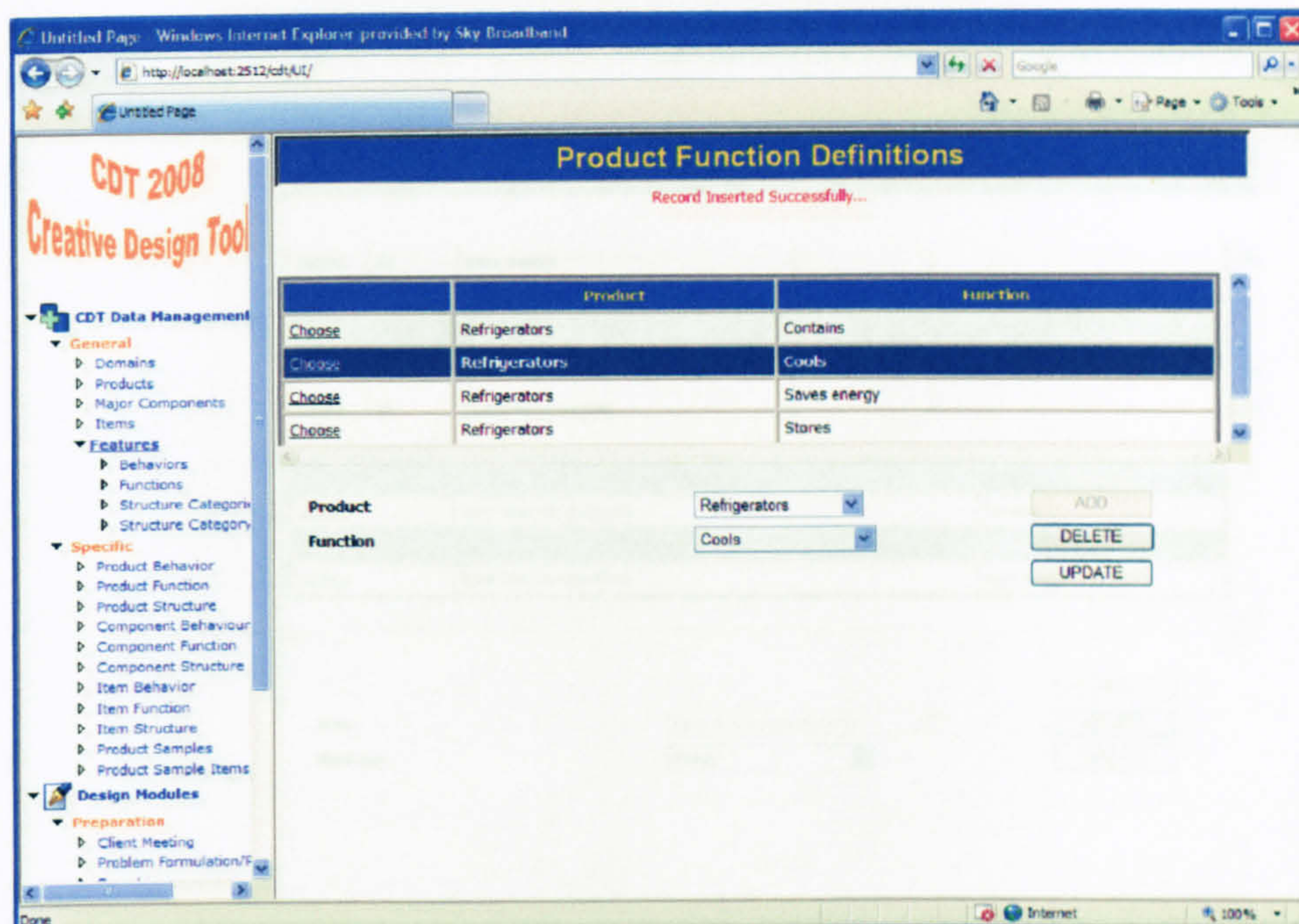


Figure 7.8 Product function definitions window

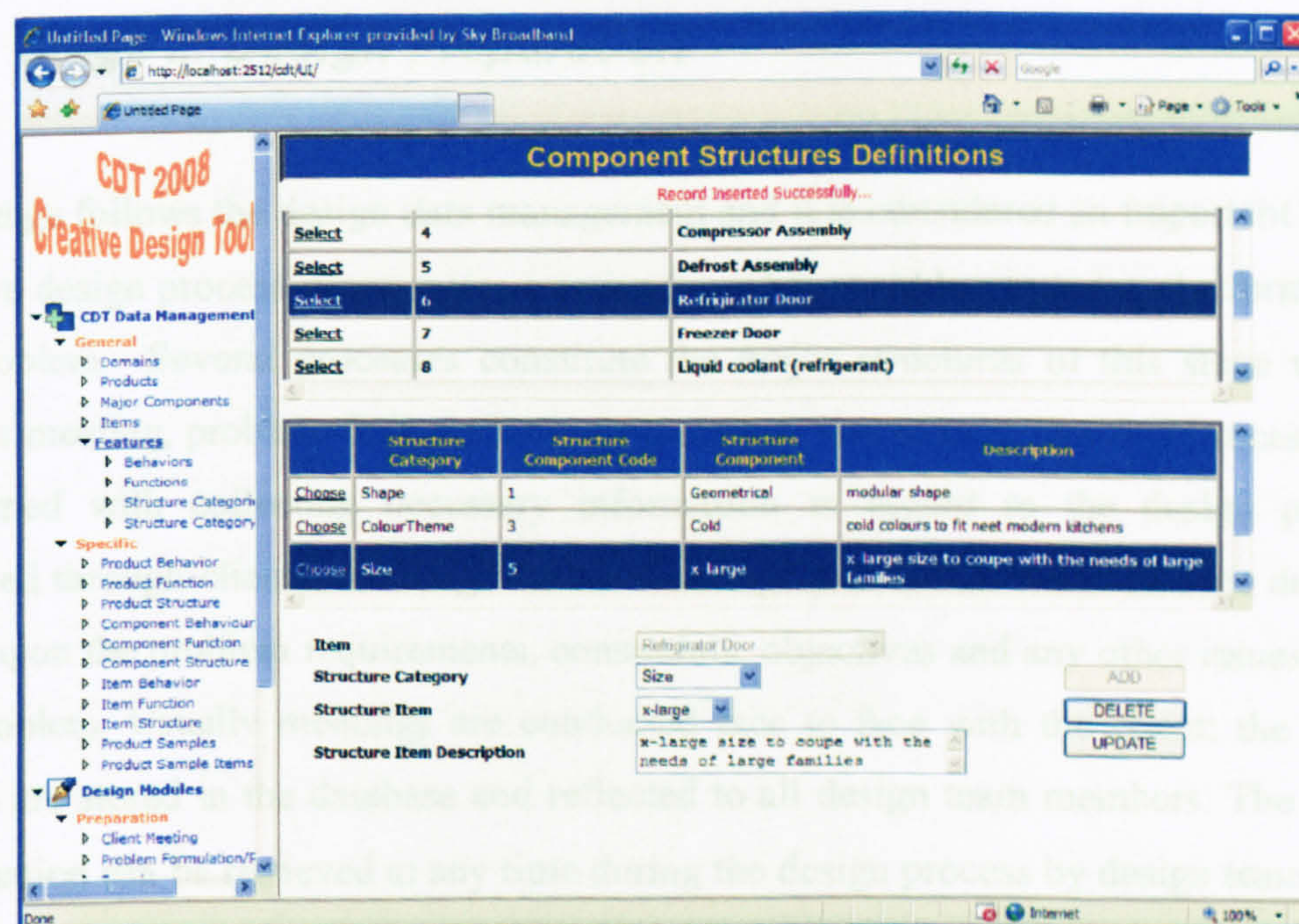


Figure 7.9 Component structures definitions window

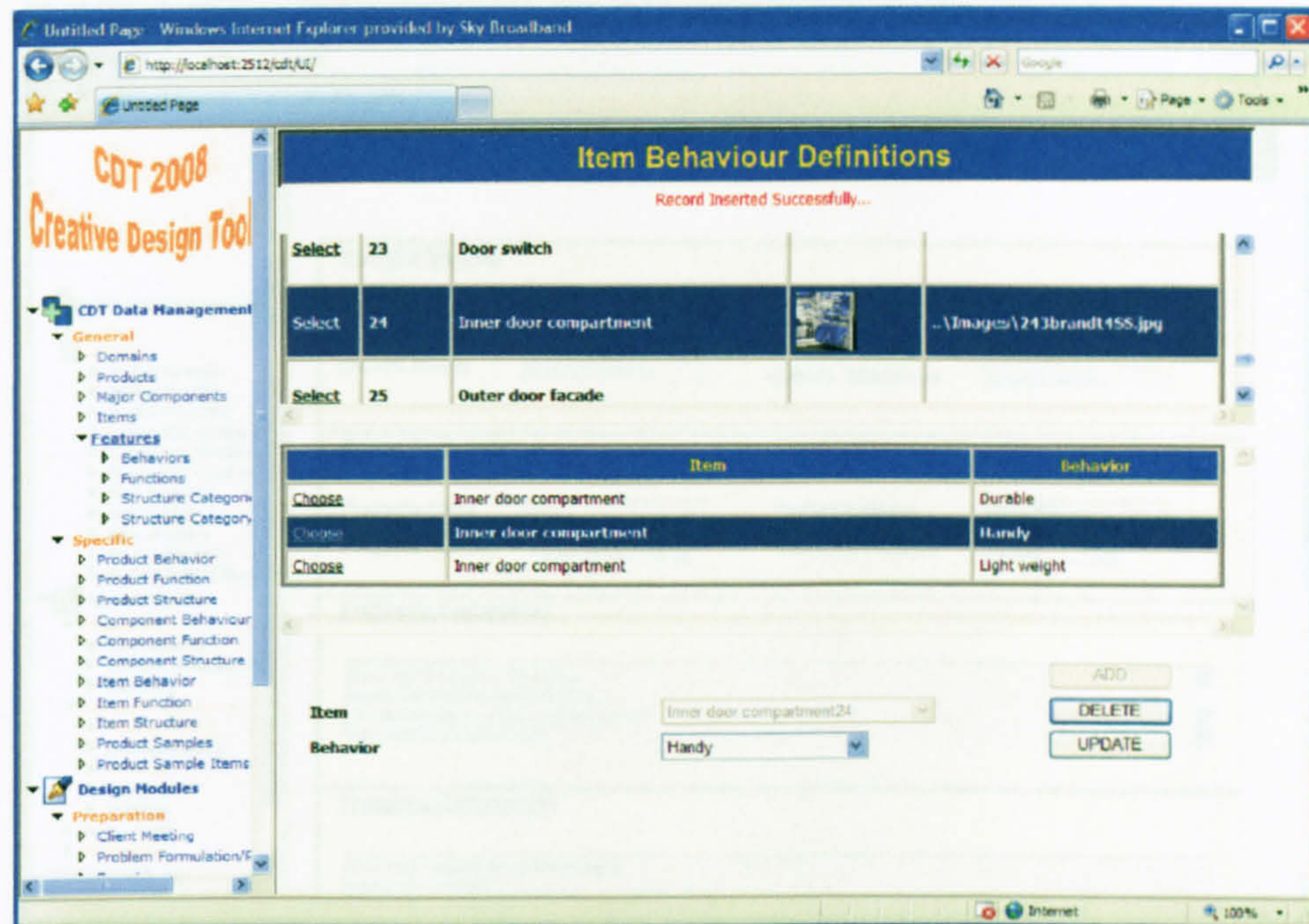


Figure 7.10 Item behaviour definitions window

7.6 Stage 2: Design Preparation

This stage follows the design data management and it is considered an important part in the creative design process, since many creative thoughts could be started in the formulation of the problem. Several processes constitute the major structures of this stage which are: client's meeting, problem formulation/reformulation, and search. The first process which is concerned with collecting necessary information in regard to the design problem is achieved through clients' meetings. Those meetings provide the basis that the design team build upon the problem requirements, constraints, objectives and any other issues related to the problem. Usually meetings are conducted face to face with the client; the meetings' details are stored in the database and reflected to all design team members. The meetings' information can be retrieved at any time during the design process by design team members whenever needed. A client's meeting form is illustrated in figure 7.11.

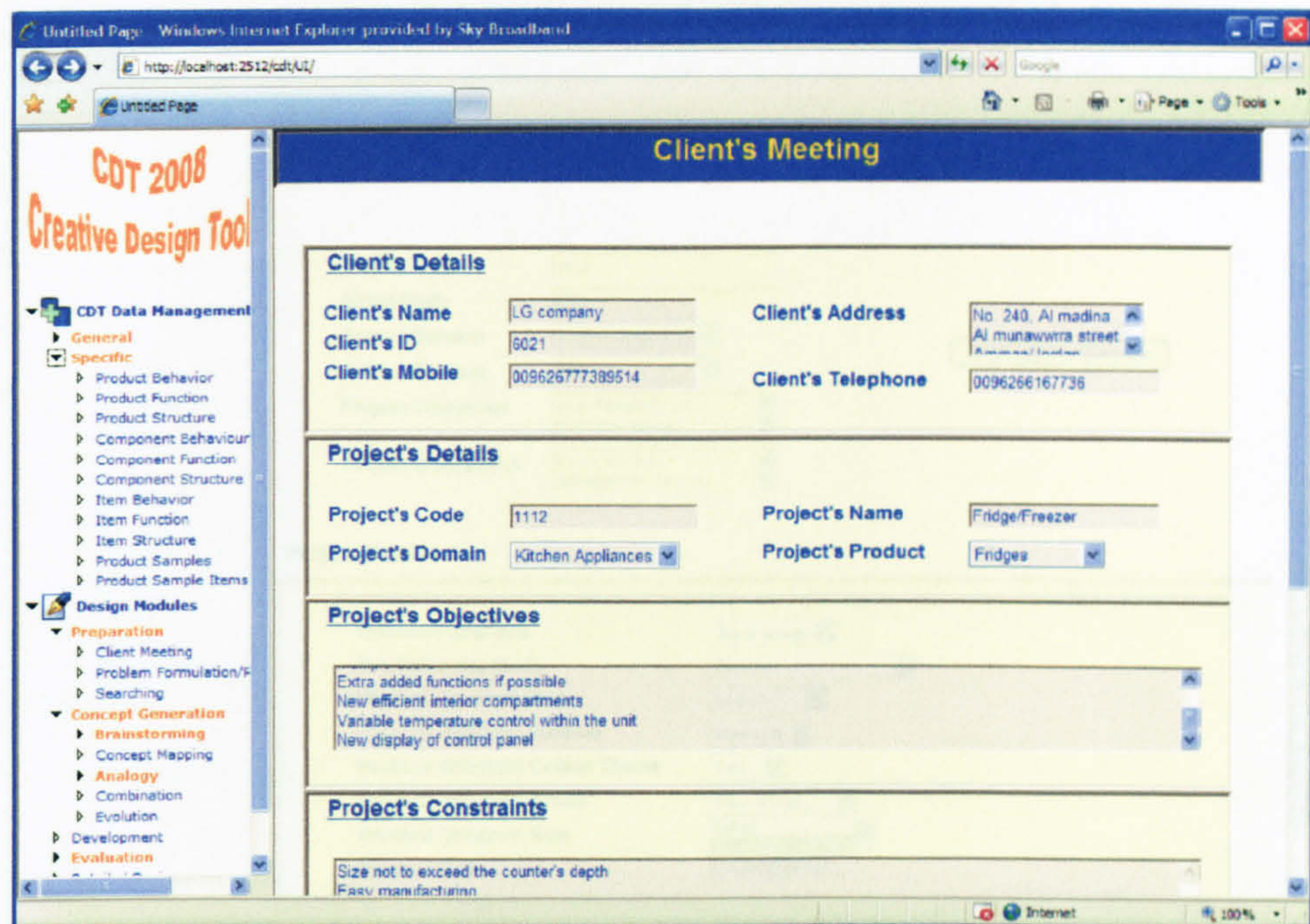


Figure 7.11 Client's meeting window

The second process is based on the client's meeting sessions where the clients' needs, likes, dislikes, and requirements are all retrieved to formulate the problem before starting the generation of concepts. A problem formulation window for the presented case study is illustrated in figure 7.12. This problem formulation step helps the designers in focusing their thinking on achieving the objectives in their proposals and introducing new requirements which they found can be useful to achieve the objectives and to generate more creative ideas. Therefore, the problem formulation/reformulation is a continuous process through the entirety of the design problem solving steps. The identified problem of the case study was to design a refrigerator with new functionalities and behaviours through the use of advanced new technologies which can service the requirements of modern kitchens and enhance the activities undertaken in such a busy zone of the house.

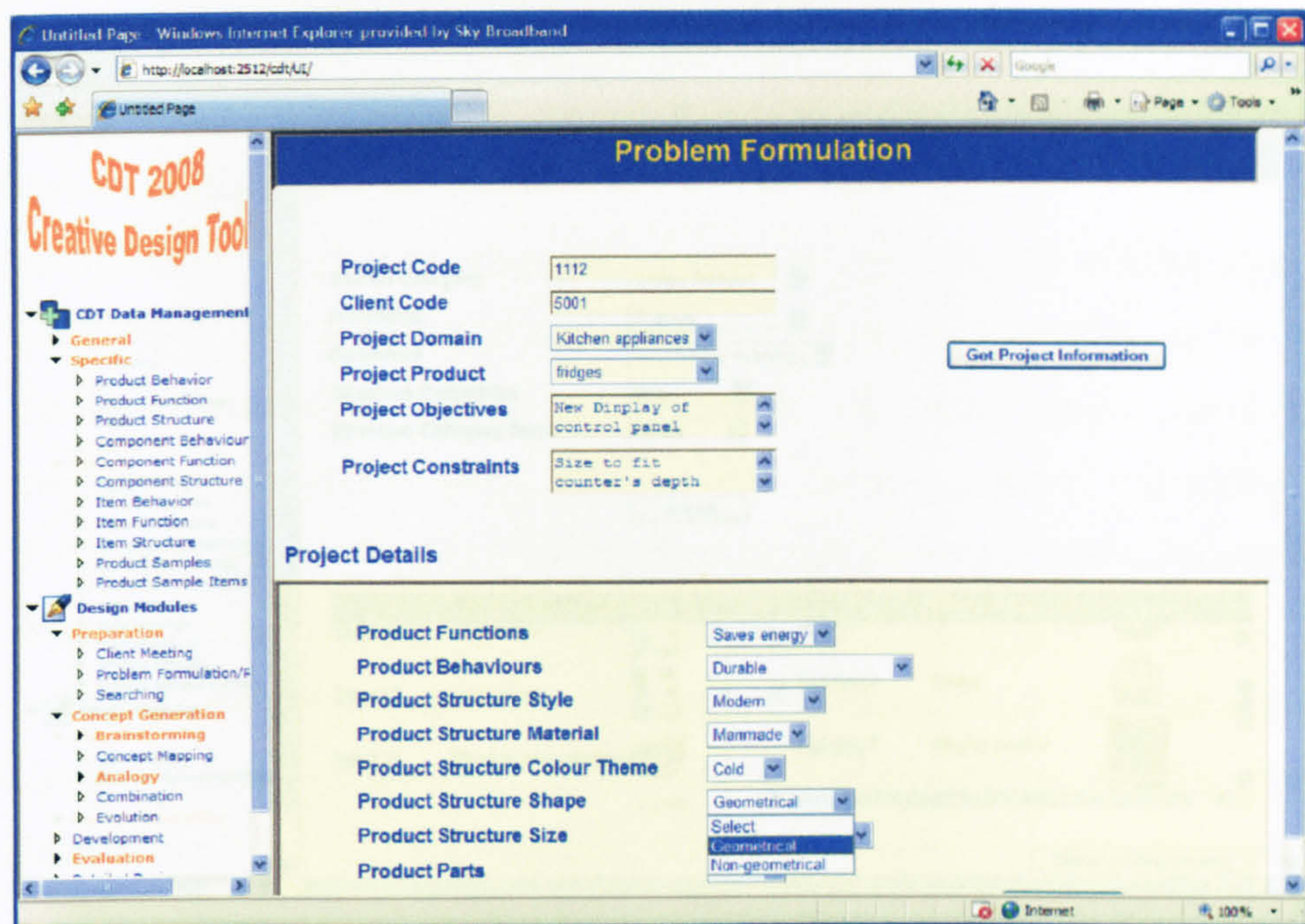


Figure 7.12 Problem formulation window

Search is the third process in the preparation stage. Designers search for data and information related to the design problem. They can retrieve sample solutions from the databases, sample components, or sample items based on specific features' constraints related to the problem. All relevant retrieved data which is recognized as being useful for the design problem is stored in the active project database to assist the generation of conceptual design solutions. Furthermore, more searches can be conducted using the World Wide Web (WWW) or any other documents the design team possesses, such as technical data of various components, materials or any other relevant information. An example window of search process is illustrated in figure 7.13.

The design data and knowledge has been added to the developed CDT system. The problem has been identified and search conducted to collect the most suitable information for further developments. At this stage the design team is ready to start the generation of conceptual design solutions for the design problem of the case study by representing the design knowledge using the various incorporated creative tools.

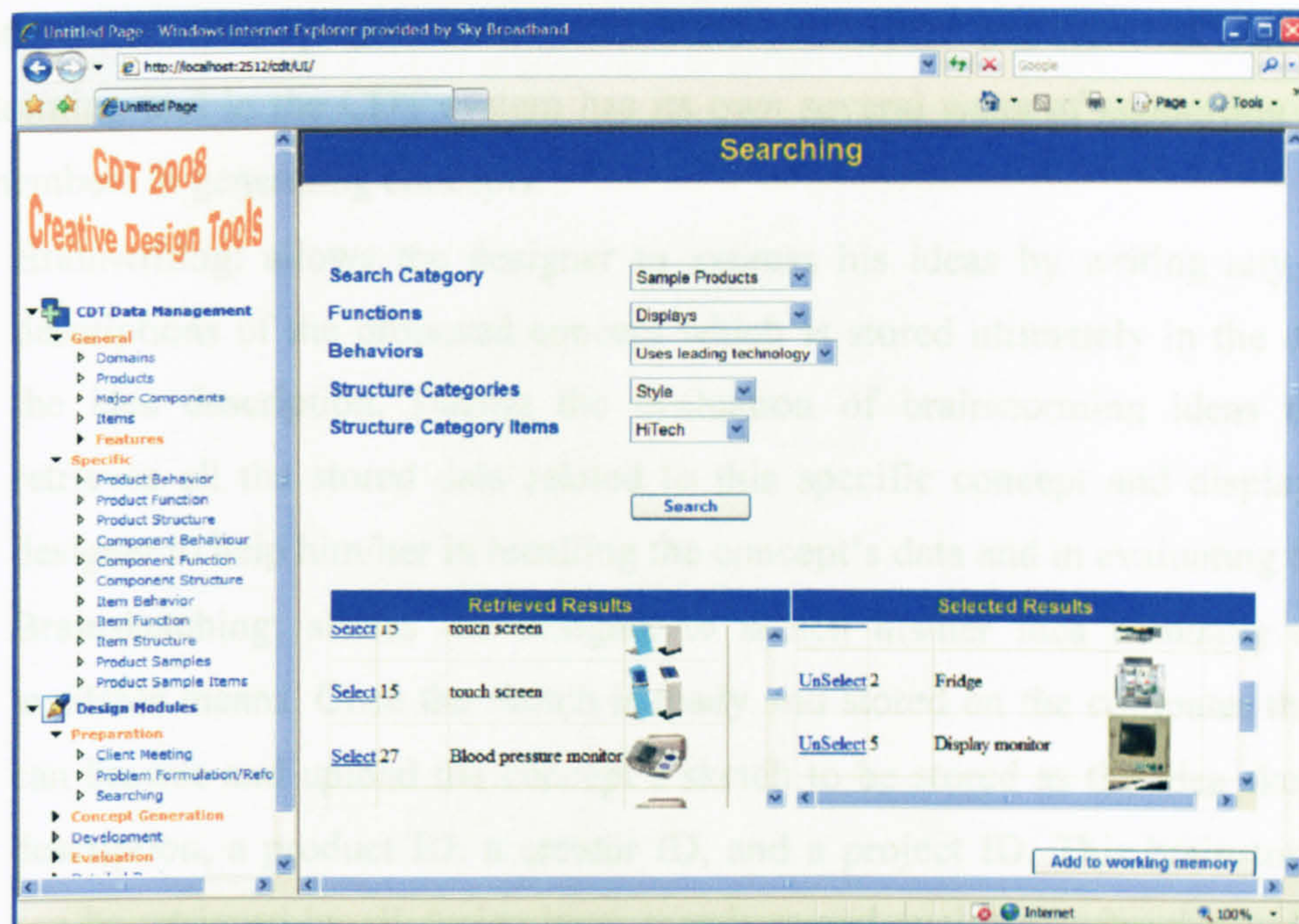


Figure 7.13 Example searching window

7.7 Stage 3: Concept Generation

The stage of concept generation is to start creating conceptual ideas to achieve the objectives of the problem by utilizing the various incorporated creative tools. Each tool has its own structure, capabilities, and ways of displaying the design options. Some are used to create new ideas and define the hierarchical structure of those ideas. Others are used to explore more options either by using the newly created options or already stored samples in the database.

7.7.1 Brainstorming

One of the most useful and successful tools in creating new ideas is brainstorming. Designers create as many ideas as they can, no criticism is allowed. All the generated ideas

are stored in the active project database for future evaluation and retrieval. The developed brainstorming tool in the CDT system has its own several ways of supporting the design team members in generating concepts:

- **Brainwriting:** allows the designer to express his ideas by writing any notes and descriptions of the proposed concept which is stored ultimately in the database as the idea description. During the evaluation of brainstorming ideas the system retrieves all the stored data related to this specific concept and display it to the designer to help him/her in recalling the concept's data and in evaluating the idea.
- **Brainsketching:** allows the designer to sketch his/her idea manually or by any available means. Once the sketch is ready and stored on the computer the designer can browse and upload the concept's sketch to be stored as the idea sketch with a description, a product ID, a creator ID, and a project ID. This brainstorming data can be retrieved by all design team members and evaluated after the brainstorming sessions have stopped. Figure 7.14 illustrates a brainstorming window with brainsketching and brainwriting of a design alternative with new functions for the refrigerator case study.
- **Brainrelating:** is another way of viewing the concept's relations using geometrical hexagon shapes. A ready developed tool in the market Axon2008 has been used for brainrelating in the CDT brainstorming. Hexagon shapes represent the different parts of the concept and by attaching the hexagon shapes together; the related parts are viewed easily. This hexagon relating diagram can be stored in the database and linked with its generated idea. An example of the hexagon brainrelating diagram is illustrated in figure 7.15 displaying one of the case study's proposed design related functions.

The brainstorming tool window is designed to provide designers with options that can facilitate his/her work. By a click on a button the designer can open a calculator application, Axon2008 application, CAD application, outlook application, search the internet, and create concept maps by navigating to the concept mapping tool.



Figure 7.14 Example brainstorming showing a new refrigerator alternative

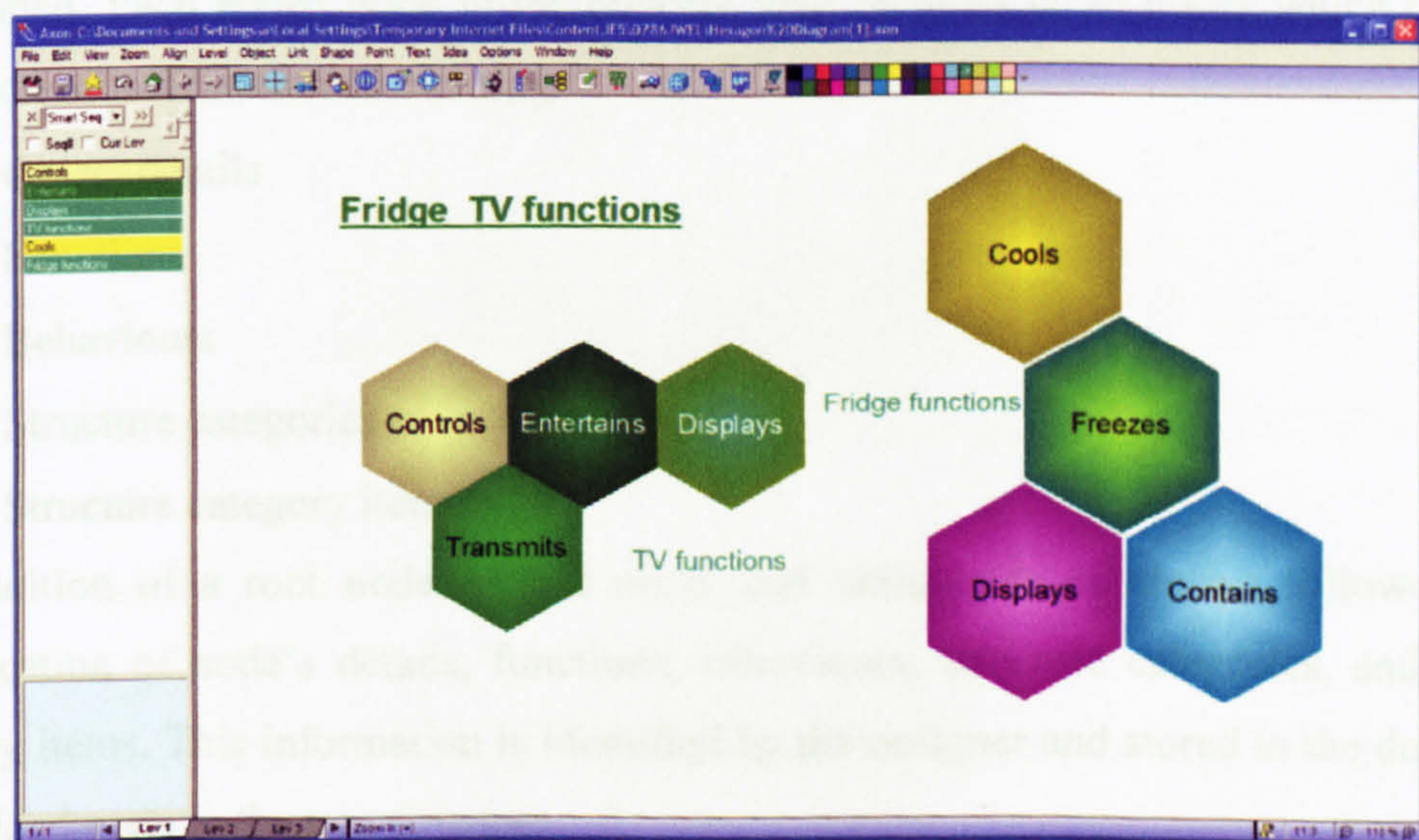


Figure 7.15 Example Axon2008 window showing new concept functions

7.7.2 Concept mapping

The concept mapping tool in the CDT system has been developed taking into consideration the hierarchical structure of any product to be designed. It assists designers in visualizing their ideas using tree hierarchical structures. Each generated idea can have its own concept map which is stored in the database and can be retrieved at any time for visualizing, and updating. This tool has two main objectives: the first is to identify the structure of the different components of the generated idea with its features and characteristics and store them in the database for further utilization by other tools and designers; the second is to be able to visualize the idea's structure hierarchy which gives a broader prospect of the generated idea.

The procedure for constructing a new concept map tree starts by adding the main concept root node which defines the scope of the created concept map. This is followed by defining the different components of the concept map by adding more parent nodes to the root node. Each component has several items which are defined by adding child nodes until all items are defined. Each added node in the concept map includes child nodes which embrace a collection of information concerning:

- Object details
- Functions
- Behaviours
- Structure categories
- Structure category items

The addition of a root node, parent node, and child node is always followed by the identification of node's details, functions, behaviours, structure categories, and structure category items. This information is identified by the designer and stored in the database for each added node in the tree structure.

The concept map tool has the option of retrieving existing maps from the database by selecting the object type to display if a sample product, a sample component, or a sample

item. Then the object is selected from a drop down menu and displayed in a tree hierarchical structure showing its all details and features. Various actions can be conducted by a click on a button such as adding a root node, adding a parent node, adding a child node, linking nodes to various types of files or images, moving the nodes up or down within the tree structure, saving the concept map, deleting a node or the concept map as a whole, and creating a new concept map. These included options facilitate the creation of a new concept map as well as updating existing ones. An example concept mapping window is illustrated in figure 7.16.

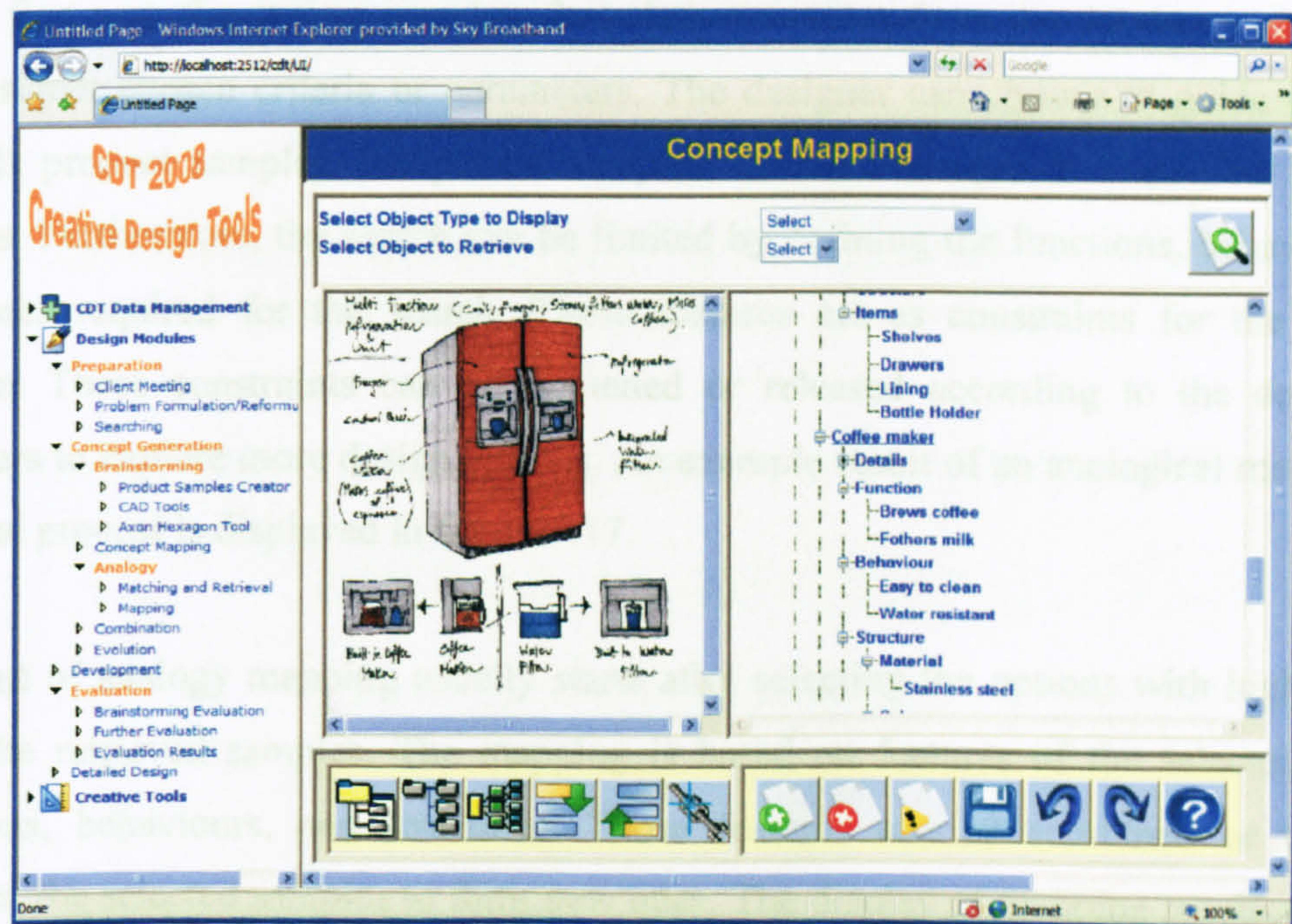


Figure 7.16 Example concept mapping showing a refrigerator alternative

The stored data of concept maps can be retrieved by other incorporated creative tools for more exploration of ideas. Therefore, the concept map tool is a major part in the developed CDT system to represent the design knowledge in a form which is clear and easy to understand by design team members and useful for the application of creative tools methods.

7.7.3 Analogy

Following the generation of new concepts and the representation of design knowledge using the previously discussed tools, more design options need to be explored. This exploration can be based on the newly generated concepts and/or on the previously stored samples in the databases. The developed analogy tool is one of the incorporated tools in the CDT system to explore design options. It is divided into two major parts: analogy matching and retrieval, and analogy mapping.

In the first part, the system searches for relative samples from the databases according to the designer chosen criteria or parameters. The designer can choose to guide the system towards product samples, component samples, or items sample to search for analogical options. Furthermore, the search can be limited by defining the functions, behaviours, and structures required for the search. These features act as constraints for the searching process. These constraints can be tightened or released according to the design team members to explore more design options. An example result of an analogical matching and retrieval process is displayed in figure 7.17.

The part of analogy mapping usually starts after selecting the options with high potential from the retrieved samples. The mapping is based on features of the selected samples: functions, behaviours, and structures. Those features can be combined or transferred between the selected samples to form new ones. The display of mapping results can reveal some potential concepts which did not emerge to designers previously. Some examples of retrieved objects and mapping results are illustrated in figures 7.18 and 7.19 respectively. Several iterations of analogical matching, retrieval, and mapping can be started to reach a potential result which can trigger a hidden creative idea.

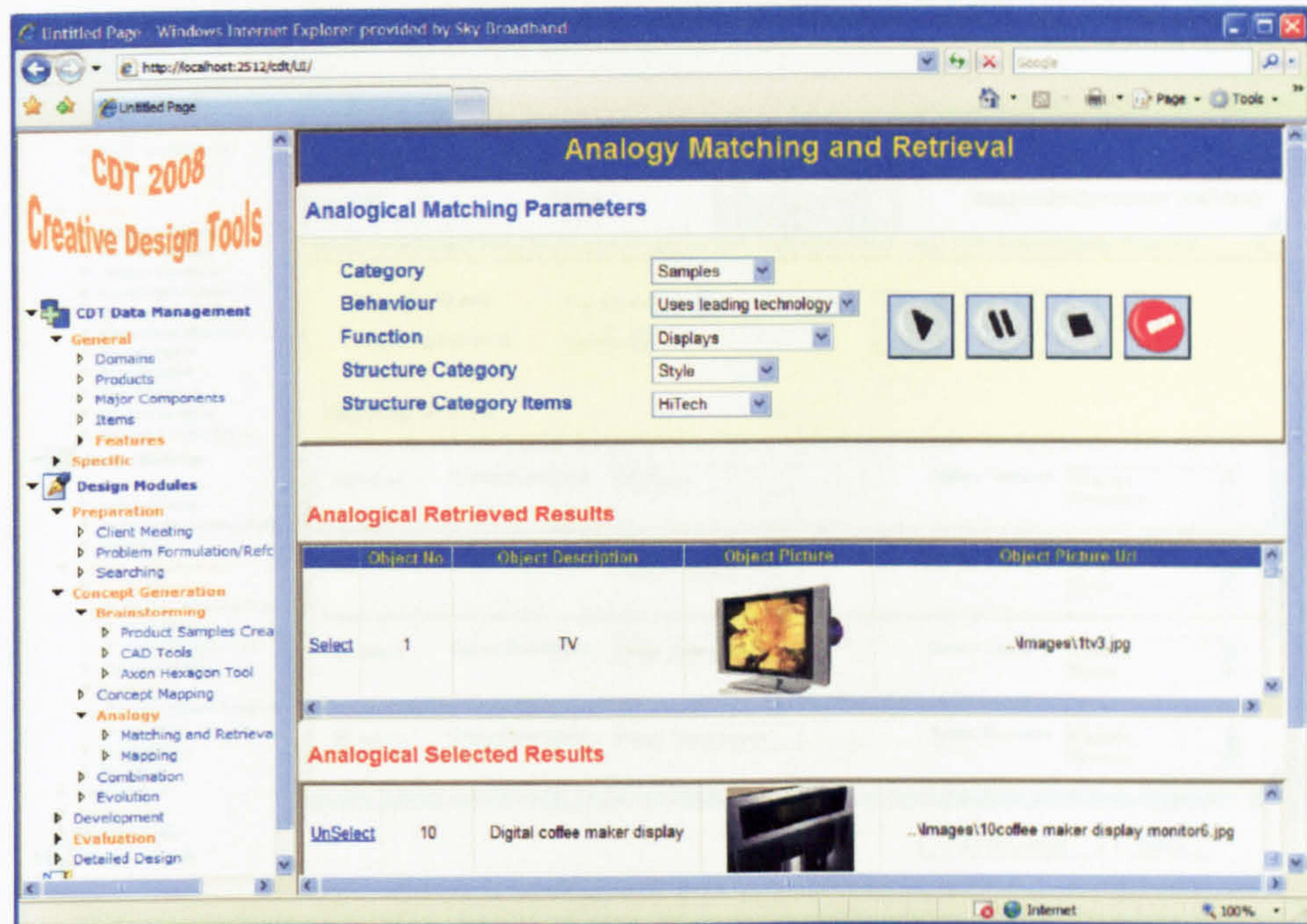


Figure 7.17 Example analogy matching and retrieval tool



Figure 7.18 Example analogy mapping tool showing the retrieved results

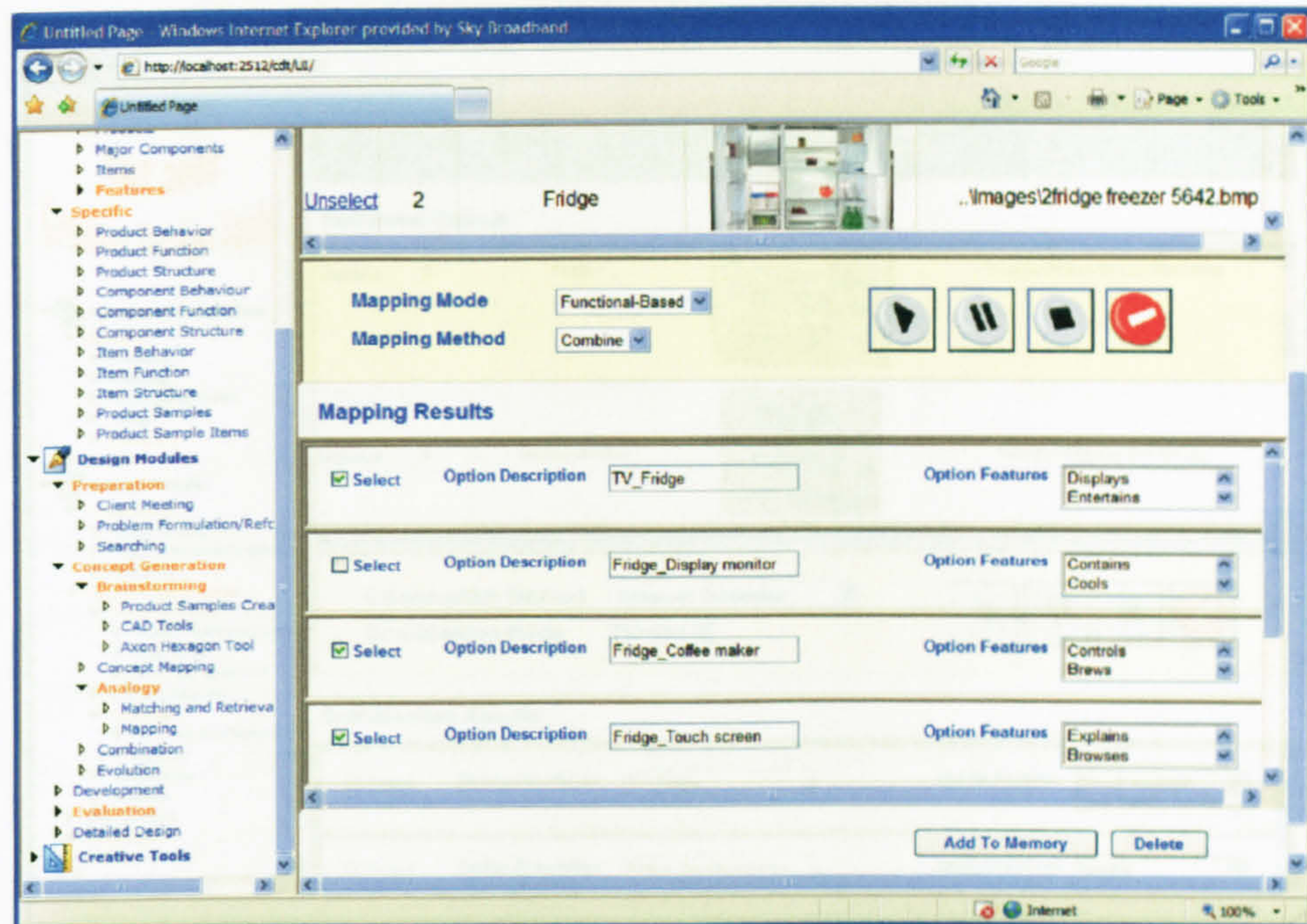


Figure 7.19 Example analogy mapping tool showing mapping results

7.7.4 Combination

Exploration of more design options continues in the combination tool. This combination tool uses the tree hierarchical structure of design alternatives to perform its methods. The idea behind it is to combine two or more objects to create a new one. It can be at any level of the tree structure, a whole product, a component, or an item. The designer retrieves some options from the created alternatives or the mapped ones from analogy to start combination and the system displays the results. Those results can be used to develop design solutions if recognized as creative. This tool implementation is still in its basic form and more development needs to take place. Two of the proposed combination methods have been implemented in the developed system and applied to some examples to validate its capabilities in the future. Figures 7.20 and 7.21 illustrate example retrieved objects and results of the implementation of the combination tool respectively.

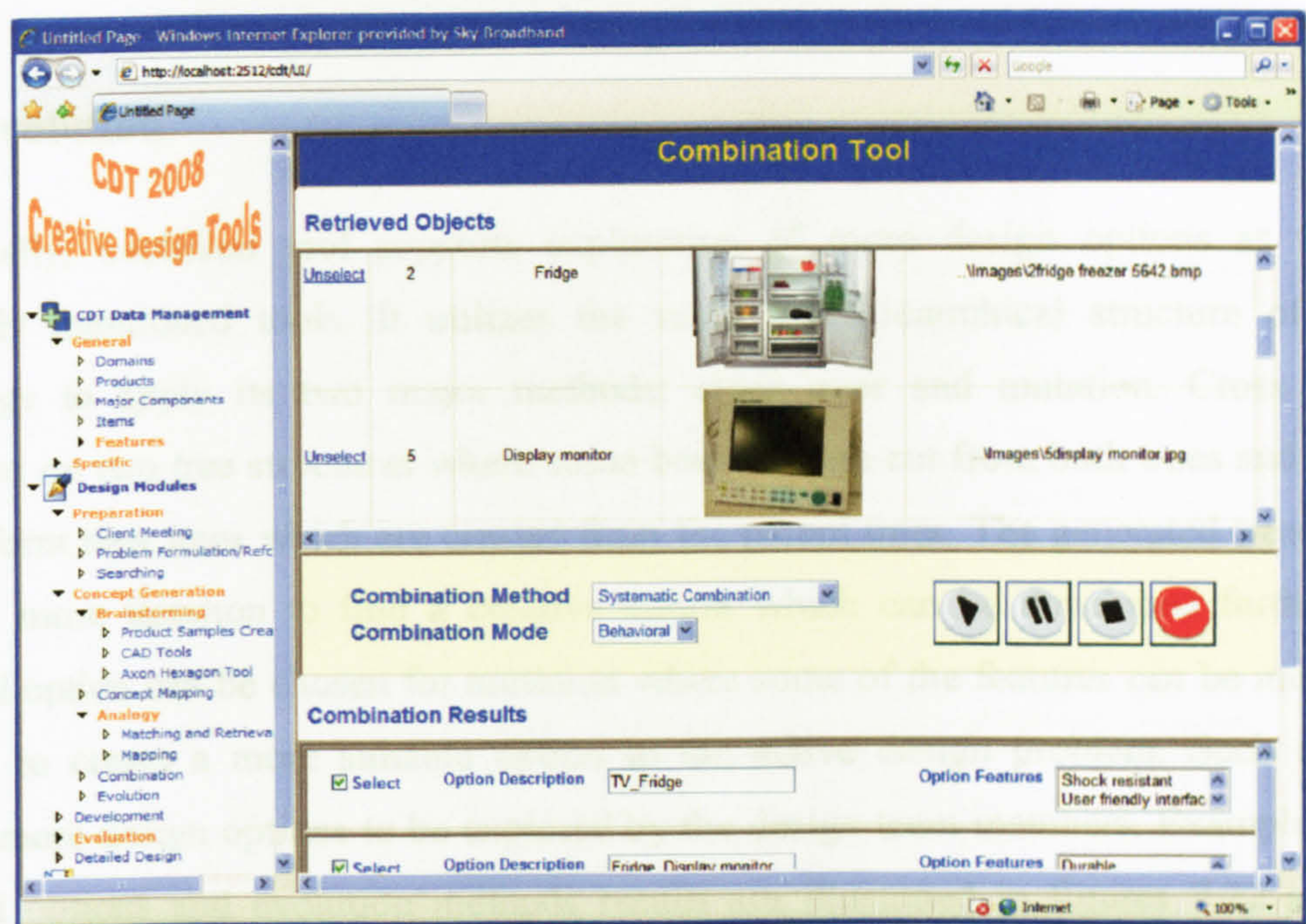


Figure 7.20 Example combination tool showing retrieved objects

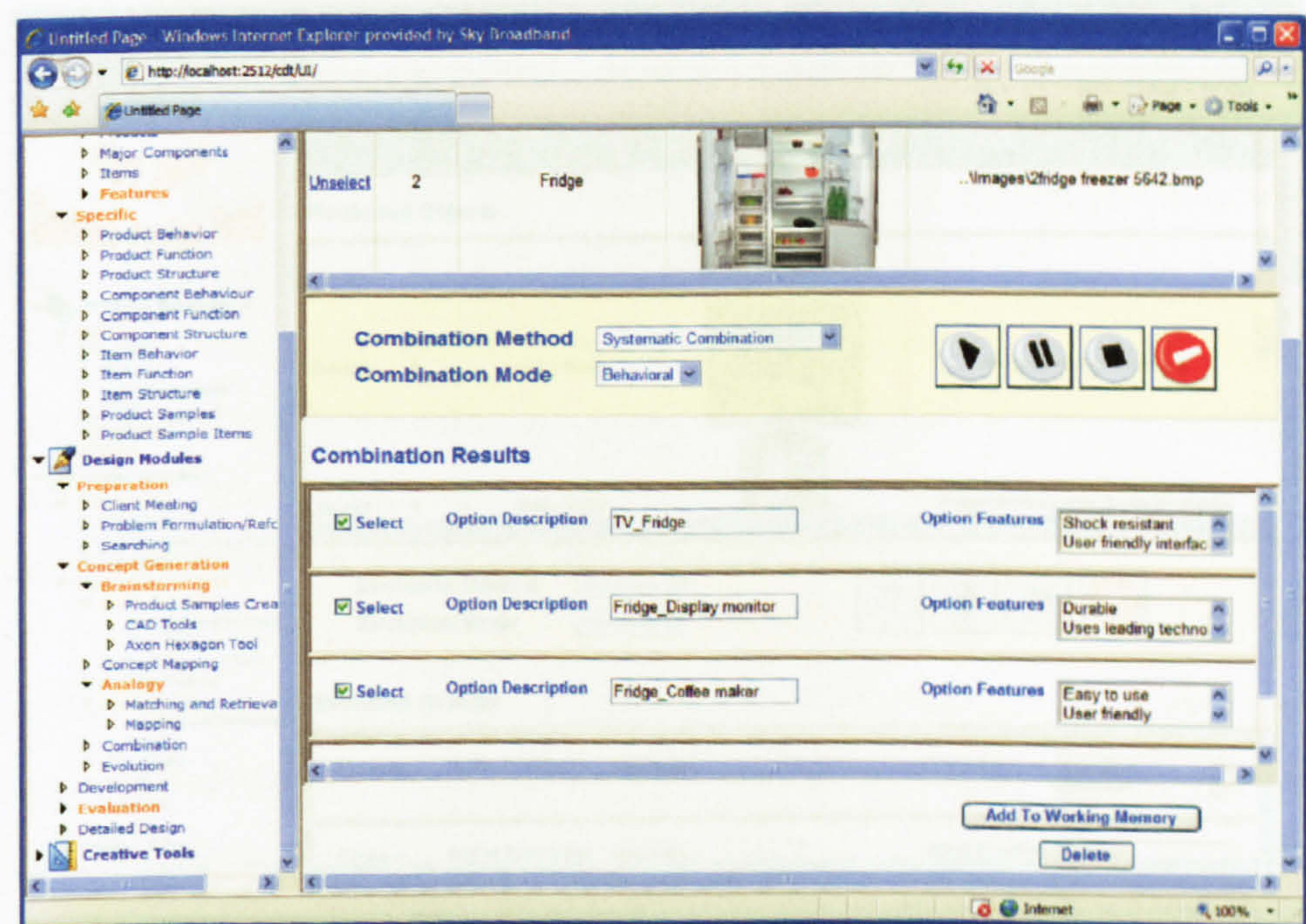


Figure 7.21 Example combination tool showing combination results

7.7.5 Evolution

Additionally, evolution tool supports exploration of more design options as the two previously mentioned tools. It utilizes the same tree hierarchical structure of design knowledge to apply its two major methods: cross over and mutation. Cross over is conducted on two tree structures where some branches are cut from both trees and crossed over to form new trees which are created from the parent trees. The generated trees can be used for more iteration to find a creative option which can be developed further. Any preferred option can be chosen for mutation where some of the features can be mutated or changed to create a more suitable option to the active design problem. Such methods provide more design options to be explored by the design team members. Examples of the retrieved options and evolution methods results are illustrated in figures 7.22 and 7.23 respectively. More detailing is still required in the application of this tool and more examples are needed to validate its capabilities in the future.

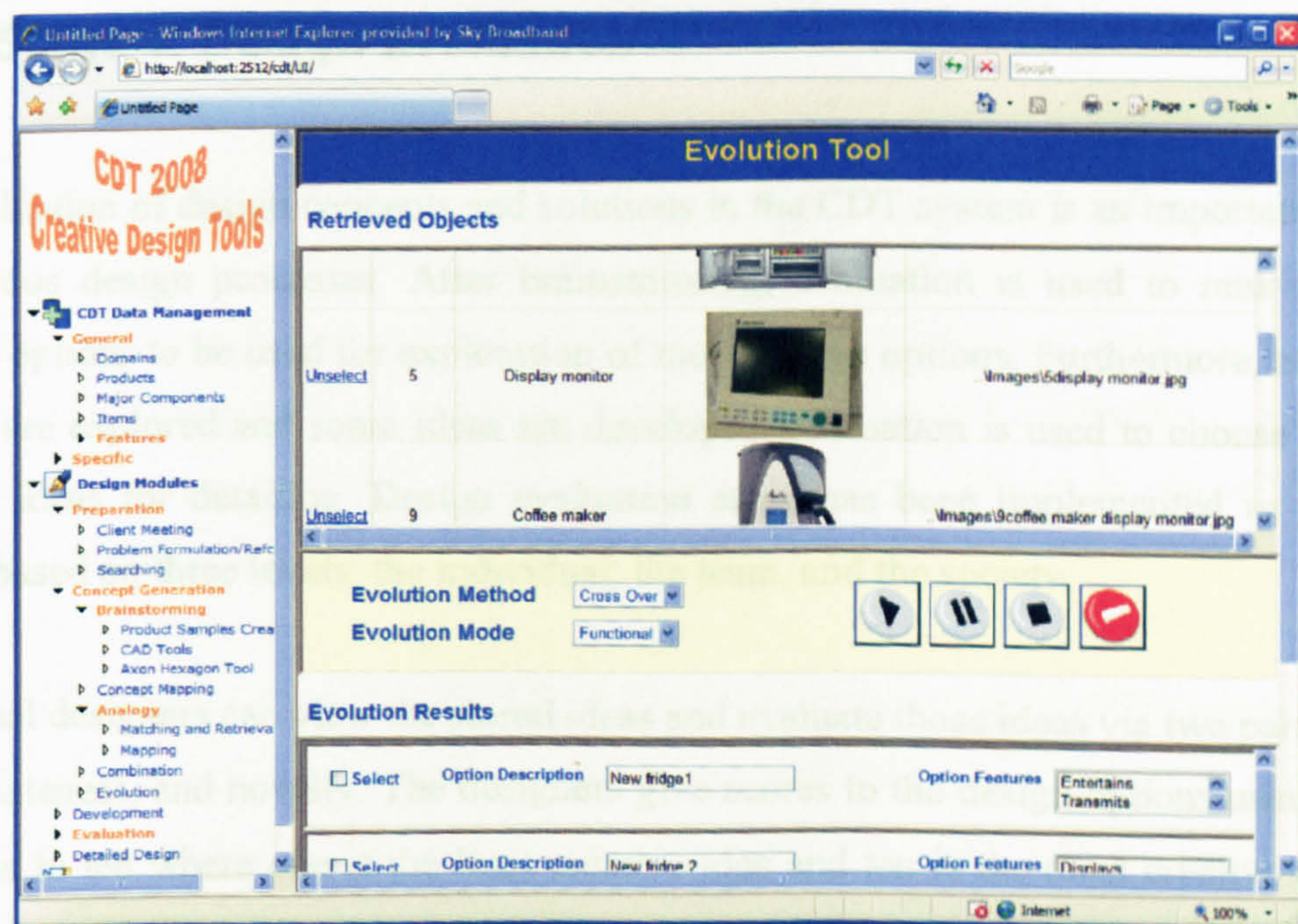


Figure 7.22 Example evolution tool showing retrieved objects

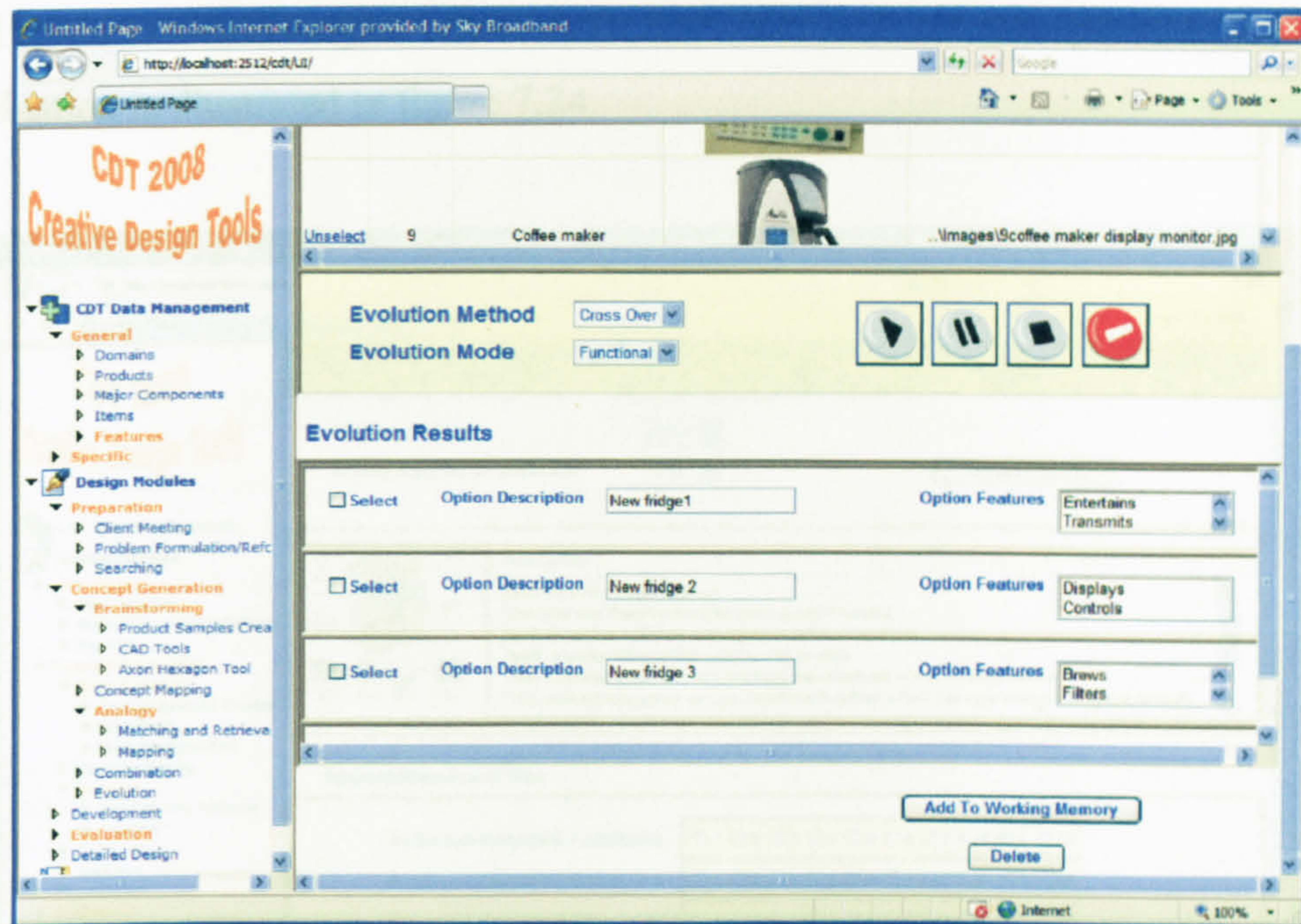


Figure 7.23 Example evolution tool showing evolution results

7.8 Stage 4: Design Evaluation

The evaluation of design concepts and solutions in the CDT system is an important stage at the various design processes. After brainstorming, evaluation is used to rank the most creative options to be used for exploration of more design options. Furthermore, after more options are explored and some ideas are developed, evaluation is used to choose the most creative ideas for detailing. Design evaluation stage has been implemented in the CDT system based on three levels: the individual, the team, and the society.

Individual designers can view the stored ideas and evaluate those ideas via two part criteria: appropriateness, and novelty. The designers give scores to the design options using a scale from one to ten where one is the least creative idea and ten is the most creative one. The evaluation result for each design idea is stored in the database and associated with the idea

data and the individual designer whom evaluation is stored. An example of a brainstorming idea evaluation is illustrated in figure 7.24.

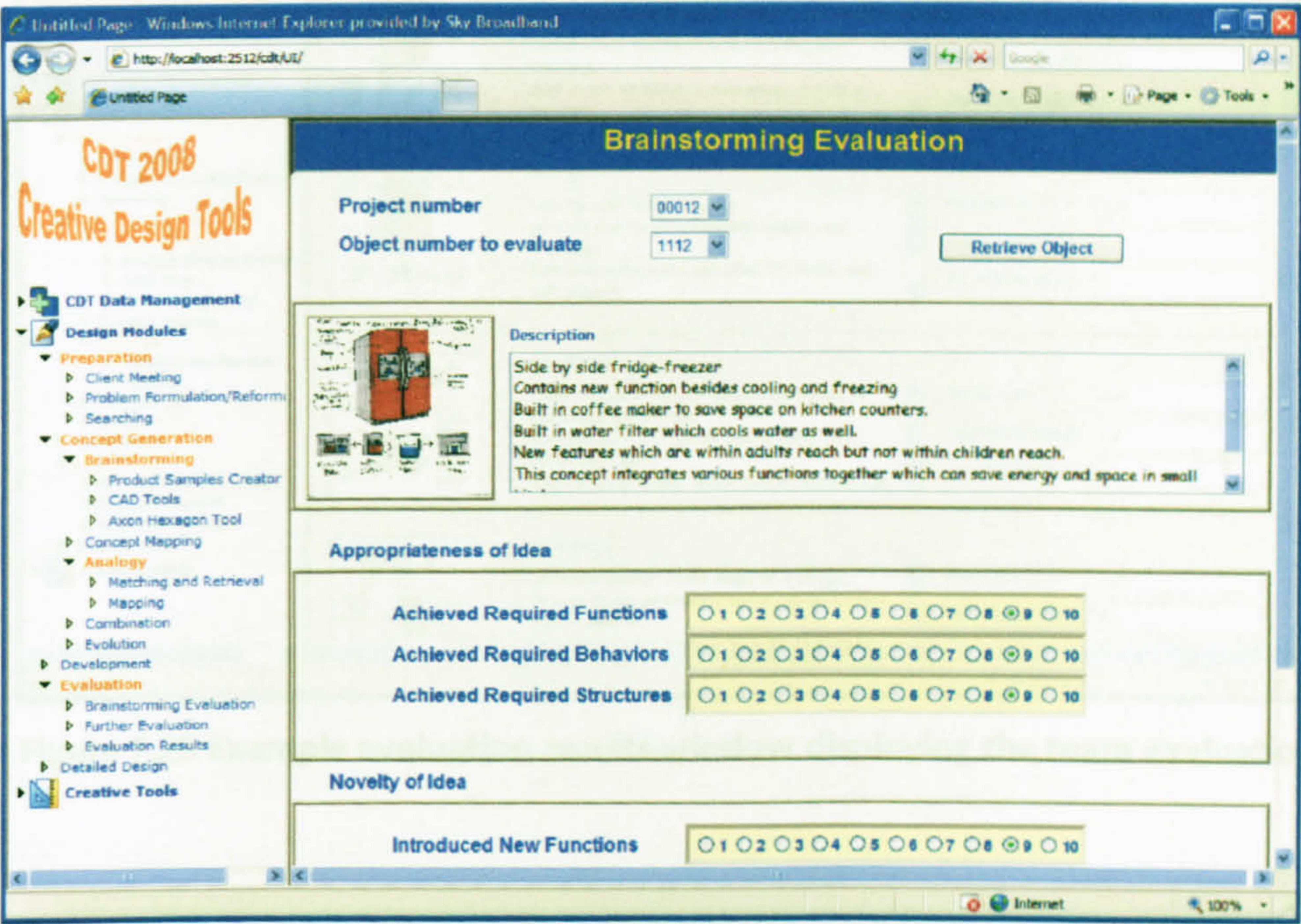


Figure 7.24 Example brainstorming evaluation window

After each individual designer has entered his evaluation scores for the stored ideas, the scores of all individuals are combined and an average for each design idea is calculated based on the individual results attained. Evaluation results of all the created concepts can be displayed to all users showing the idea description, image, and evaluation score. This is called the team evaluation level. Figure 7.25 illustrates an evaluation results window with various evaluated design ideas.

The final stage in the design evaluation is the society evaluation. In this stage evaluation scores from other individuals such as clients and managers are collected to get a wider scope of the creativity of the generated design concepts. Any generated idea which is considered creative in the three evaluation stages constitutes a strong candidate for further development.

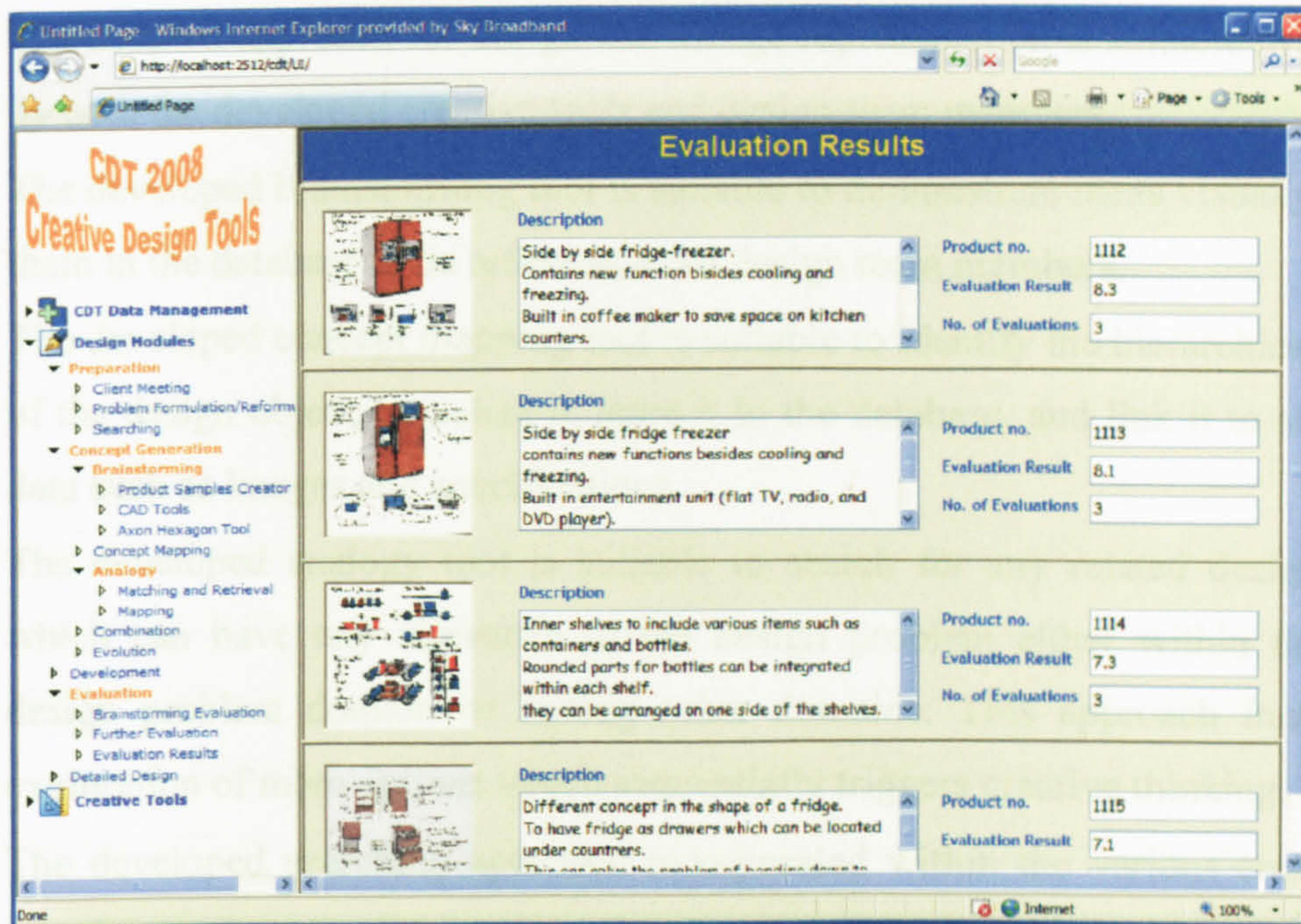


Figure 7.25 Example evaluation results window displaying the team evaluation

7.9 Discussion

The developed CDT prototype system has been validated in this chapter through the application of four design stages. The integration of design team members, design processes, creative tools, knowledge, and computation has been demonstrated. The case study was important in validating the features of the developed CDT system:

- The development of the CDT system as a web application is suitable to facilitate collaboration among design team members. Any defined data, new ideas, and changes are reflected immediately to all design team members which saves time and effort.
- The approach of CDT data management makes it flexible to be used by various design disciplines to solve any given design problem because design team members can identify the data they require for each design problem.

- The adopted approach for design knowledge representation is suitable to be utilized by both the developed creative tools and design team members.
- The developed brainstorming tool is suitable to demonstrate ideas visually and store them in the database to be reflected to all design team members.
- The developed concept mapping tool is suitable to identify the hierarchical structure of the design object, visualize it, store it in the database, and link it to any relative data such as images and specifications.
- The developed analogy tool is suitable to search for any related design samples which can have any relevance to the design problem either within the specific design problem domain or among other domains. This approach increases the exploration of more options which sequentially triggers creative thinking.
- The developed searching approach incorporated within the various creative tools uses features' constraints as a searching criterion. It is suitable to be either tightened or released according to the designers' preference through the GUI.
- The developed combination and evolution tools are suitable for more design explorations when finalised.
- The implemented evaluation approach demonstrates the importance of the individual, team, and society in the evaluation process and how they influence the recognition of creative ideas.

The integration of all the previously mentioned features provides a creative design environment for design team members to facilitate and enhance their creative thinking through exploration of novel ideas, new ways of visualization of design knowledge, and collaboration.

7.10 Summary

The developed CDT Creative Design Tools prototype system has been validated using a case study from the kitchen appliances industry. The case study has demonstrated many of

the capabilities of the developed system in identifying new design data, representing design knowledge, generating new design alternatives, exploring various design options by using incorporated creative tools, and evaluating the created ideas. The implemented case study has shown that the CDT system has potential for enhancing the creative design thinking among design team members through exploration of more design ideas, collaboration, and new ways of design knowledge visualization.

Holistic approach to enhance creative design thinking through the conceptual design phase is made possible. The integration of various creative tools within a shared design environment facilitates collaboration among design team members to produce more creative ideas, evaluate them, and select the most appropriate ones to be developed and detailed for production. The early evaluation of design concepts minimizes the lead time for industry since the inappropriate ideas are eliminated early in the design process. Therefore, reductions in conflicts and inconsistencies at later design stages are achievable and the production of more creative ideas is viable.

The system has shown an innovative approach to integrate several factors which affect creative design thinking namely:

- Distributed design team members.
- Design knowledge representation.
- Creative thinking tools.
- Design processes.

CHAPTER EIGHT

OVERALL CONCLUSIONS

8.1 Overview

The research work described in this thesis contributes to the philosophy of design by combining various creative design concepts, methods and tools using evolutionary computation and visualisation technology. The developed architecture supports designers both conceptually and computationally through the whole design process. The intention is to provide designers with all the support they need in their design problem solving processes to explore more design options and enhance their creative thinking in collaborative design environments, thereby significantly producing more creative design solutions and reducing lead-times. This was achieved by the use of Web technologies to develop an integrated and flexible design environment for designers wherever located.

The literature review indicated that all previous research studies in this area lack a holistic perspective of creative design. They have discussed individual issues in creative design but ignored the humanistic influence on such systems. Several of the identified frameworks for creative design were focussing upon a specific tool or approach and lack the holistic approach to the problem. Hence they have been unable to provide the basis for a holistic, realistic, practical, and well integrated computing system for the entire design process. The area of creative design thinking needs to be addressed from a holistic perspective than the previous endeavours have considered. Existing creative design environments are limited in terms of integration of creative tools, processes, and required knowledge. This requires full consideration of creative thinking facets and integration of various tools, techniques, processes, and knowledge within a flexible human design environment.

The need for such a holistic approach to enhance creative design thinking by providing an integrated flexible design environment with the proper knowledge, processes, and creative

tools proved to be a necessity and since design is a nonlinear process a concurrent design platform can be useful in such systems.

This research work accomplished several fundamental issues in creative design environments. These accomplishments are as follows:

- Many creative tools which were found to be useful in the literature for creative design thinking are computationally improved, specified, and integrated within a flexible environment which can be used by various design disciplines.
- A flexible hierarchical design representation is constructed and implemented in the proposed CDT system which is easy to comprehend by designers and to be used by computational creative tools to explore more design alternatives.
- The developed procedures for the creative tools incorporated in the proposed CDT system facilitate the constraints manageability by the designers. Designers can choose the constraints they require according to data identified or from the databases already in existence. This achieves the highest flexibility between the designers and the system and integrity between the various components of the proposed CDT system.
- The implementation of the proposed CDT system as a web application achieved several advantages over other system's applications.
 - Firstly, changes in the data and generated designs are reflected immediately to the authorised users whenever and wherever they use the system which provides similarity in the data retrieved.
 - Secondly, collaboration is more efficient through direct access to similar design knowledge at any time.
 - Thirdly, it provides consistency in the user interface and knowledge for all authorised users.
 - Fourthly, it minimizes effort and cost in system maintenance which can be conducted at one single station and reflected to all users.

- The creative tools improved and incorporated in the proposed CDT system increase the flow of concepts and widen the solution space through search. This helps in minimizing design fixation among designers by exploring more various options beyond the routine design state space which can release and create new directions for problem solutions.

8.2 Thesis Contribution

In summary the proposed work contributes much to the design development and creative design thinking for it brings together previous research from three major domains namely, design, creativity, and computation. It allows designers to search, design, evaluate, and develop their ideas within a flexible and stimulating environment. Furthermore, it enhances team work throughout the whole design process by providing the required means for inter-related design environments and evaluation process adopted. The system incorporates state of the art computational tools, and methods to assist the design teams and widen their search space. All this has been achieved by:

- Investigating existing creative design concepts, techniques, computing and visual technologies, product and spatial design processes, and the use of visual expressions in design development through literature review and interviews.
- Developing a holistic approach for creative design thinking which involves structured design knowledge, creative design tools, design processes, and people.
- Constructing the overall architecture for a creative design environment to manage complex design processes and tools that support the needs for more creative design solutions from the early stages of design.
- Developing a novel design computational model that deals with various vital issues to enhance creative design thinking among design teams.
- Overcoming the limitations of existing creative design models and providing a methodology for creative design model which integrates various creative tools,

processes, knowledge, and people, using web-technologies to support creative design collaboration.

- Developing a working prototype using state of the art web-technologies, and design computation methods.
- Validating the developed system through the application of a case study demonstrating several design stages.

CHAPTER NINE

RECOMMENDATIONS FOR FUTURE WORK

This research work has contributed much to the enhancement of creative design thinking through the implementation of a holistic approach of creative design computational environment.

On the other hand, this approach has covered a wide diversity of areas of specialization. The presented solution provides the basis for further research in creative design computational environments. It provides the framework where more detailed and improved creative tools can be incorporated, design processes can be expanded to include the finest details, and more advanced visualization technologies can be integrated. A broader framework can be developed through appropriate expansions of this research. Applicable future research work in this area of study is summarized in the following:

- The approach adopted in this research has been based upon the implementation of ASP.NET web programming technology pioneered by Microsoft to create dynamic web pages. ASP.NET technology resolved the shortcomings of ASP through the identification of common web development tasks and addition of functionality to make such tasks a cinch. ASP.NET technology can be used to connect to a variety of client implementations either in HTML, Java, or Flash. Such technologies have been improved and continue to be improved in coming years. Following up any new enhancements in technology can improve the work and solve any problematic issues in the implementation.
- The developed system incorporated some of the creative tools which were recognized as being useful to the creative design thinking. Many other tools can be incorporated in the system to extend the tools platform that the designer can

explore. Such tools can be expanded to include several concerns besides creative design thinking, such as project management, material selection, market analysis, sketching tools, and more visualization tools. This expansion can support the design team competence in addition to creative thinking.

- Sketching tools such as graphic tablets could be integrated with the system for future improvement, where the designer can use this tool to reflect the results immediately on the screen without the need to sketch manually, scan the results, and store them in the databases. This can save time, effort, and improve the design outcome.
- The prototype system developed in this research can be used as a creative design environment for enhancing creative design thinking in various disciplines. The developed system has been tested using a product design case study. However, further testing for different types of complex products should be undertaken.
- Although, the system has been developed taking into consideration product design as an application, further testing for different design disciplines should be carried out to identify the full benefits and the shortcomings of the developed system for possible future improvements. One of the areas suggested is: spatial design which includes architecture and interior design.
- This research work has assumed that the design team speaks a common language and has the same cultural background. However, in global design collaboration, there is a strong possibility that this is not the case. It was recognized that culture and society play an important role in creativity recognition from the very early design stages. Therefore, research into a multi-language and multi-cultural creative design environment would be another interesting area for future research.

REFERENCES

- AKIN, O. and AKIN, C. (1996) Frames of Reference in Architectural Design: Analysing the Hyper acclamation (A-h-a-!). *Design Studies*, 17(4), pp. 341-361.
- ANDERSON, N. (2002) *A distributed information sharing collaborative system (DISCS)*. Unpublished thesis (PhD), De Montfort University.
- ANDERSON, N. and ABDALLA, H., (2002) A Distributed E-Commerce System for Virtual Product Development Teams. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 216(2), pp. 251-264.
- AUSTIN, S., STEELE, J., MACMILLAN, S., KIRBY, P., and SPENCE, R. (2001) Mapping the Conceptual Design Activity of Interdisciplinary Teams. *Design Studies*, 22(3), pp. 211-232.
- BAXTER, M. (2002) *Product Design Practical Methods for the Systematic Development of New Products*. 3rd ed. Cheltenham, UK, Nelson Thornes Ltd.
- BENTLEY, P.J. (1997) The revolution of evolution for real-world applications. *In: Engineering Technologies '97: Theory and Application of Evolutionary Computation*, University College London, 15th December 1997.
- BENTLEY, P.J. and CORNE, D.W. (2002) *Creative evolutionary systems*. London, Morgan Kaufmann.
- BENTLEY, P.J. and WAKEFIELD, J.P. (1996) Conceptual evolutionary design by a genetic algorithm. *Engineering Design and Automation Journal*, 2(3), John Wiley and Sons, Inc.
- BODEN, M. (2007) *Creativity: How Does it Work?*, published by Creativity East Midlands for the Creativity: Innovation and Industry conference, 6th December 2007.

- BODEN, M.A. (1994) What is creativity? In: *BODEN, M.A. Dimensions of creativity*. USA, DEKR Corporation, pp. 75-117.
- BRIGGS, R. O. (2006) On theory-driven design and deployment of collaboration systems. *International Journal of Human-Computer Studies*, 64(7), pp. 573-582.
- BRUCE, M., and COOPER, R. (2000) *Creative Product Design A practical Guide to Requirements Capture Management*. 1st ed. Baffins Lane, Chichester, England, John Wiley and Sons, Ltd.
- CANDY, L. (1997) Computers and creativity support: knowledge, visualisation and collaboration. *Knowledge-Based Systems*, 10(1), pp. 3-13.
- CANDY, L. and EDMONDS E.A. (1997) Supporting the creative user: a criteria-based approach to interaction design. *Design Studies*, 18(2), pp. 185-194.
- CANDY, L., and EDMONDS, E. (1996) Creative Design of the Lotus Bicycle: Implications for Knowledge Support Systems Research. *Design Studies*, 17(1), pp. 71-90.
- CARROLL, J. M., ROSSON, M. B., CONVERTINO, G., and GANOE, C. H. (2006) Awareness and teamwork in computer-supported collaborations. *Interacting with Computers*, 18(1), pp. 21-46.
- CHA, M.Y. and GERO, J.S. (2005) Shape pattern representation for design computation. *Key Centre of Design Computing*, University of Sydney, Australia, pp.1-32.
- CHAKRABARTI, A., and BLIGH, T. P. (2001) A Scheme for Functional Reasoning in Conceptual Design. *Design Studies*, 22(6), pp. 493-517.
- CHAPMAN, C. B., and PINFOLD, M. (1999) Design Engineering- a Need to Rethink the Solution Using Knowledge Based Engineering. *Knowledge-Based Systems*, 12(5-6), pp. 257-267.

- CHEN, Y-J, CHEN, Y-M, and CHU, H-C (2008) Enabling collaborative product design through distributed engineering knowledge management. *Computers in Industry*, 59(4), pp. 395-409.
- CHUANG, M. C., CHANG, C. C., and HSU, S. H. (2001) Perceptual factors underlying user preferences toward product form of mobile phones. *International Journal of Industrial Ergonomics*, 27(4), pp. 247-258.
- CRAWFORD, M., and DI BENEDETTO, A. (2006) *New Products Development*. 8th ed. Irwin, McGraw-Hill.
- CROSS, N. (1997) Descriptive models of creative design: application to an example. *Design Studies*, 18(4), pp. 427-455.
- CROSS, N. (2000) *Engineering design methods: strategies for product design*. 3rd ed. West Sussex, John Wiley and Sons.
- CSIKSZENTMIHALYI, M. (1988) Society, culture and person: a systems view of creativity. In: *STERNBERG, R.J. (ed), The nature of creativity*, Cambridge University Press, Cambridge UK (1988), pp. 325-339.
- CSIKSZENTMIHALYI, M. (1996) *Creativity: flow and the psychology of discovery and invention*. New York, Harper Collins.
- DAHL, D. W., CHATTOPADHYAY, A., and GORN, G. J. (2001) The Importance of Visualisation in Concept Design. *Design Studies*, 22(1), pp. 5-26.
- DARLINGTON, M. J., and CULLEY, S. J. (2004) A model of Factors Influencing the Design Requirement. *Design Studies*, 25(4), pp. 329-350.
- DO, E. Y-L. (2005) Design sketches and sketch design tools. *Knowledge-Based Systems*, 18(8), pp. 383-405.
- DONG, A. and AGOGINO, A. M. (1998) Managing Design Information in Enterprise-wide CAD Using 'Smart Drawings'. *Computer-Aided Design*, 30(6), pp. 425-435.

- DORST, K. (2001) Creativity in the design process: co-evolution of problem-solution. *Design Studies*, 22(5), pp. 425-437.
- EDEN, C. (2004) Analyzing Cognitive Maps to Help Structure Issues or Problems. *European Journal of Operational Research*, 159(3), pp. 673-686.
- EYSENCK, H.J. (1994) The Measurement of Creativity. In: *BODEN, M., eds. Dimensions of Creativity*. USA, Massachusetts Institute of Technology, pp. 199-242.
- FISCHER, G. and NAKAKOJI, K. (1997) Computational environments supporting creativity in the context of lifelong learning and design. *Knowledge-Based Systems*, 10(1), pp. 21-28.
- GARDNER, H. (1994) The Creators' Patterns. In: *BODEN, M., eds. Dimensions of Creativity*. USA, Massachusetts Institute of Technology, pp. 143-158.
- GERO, J. (1990) *Design prototypes: a knowledge representation schema for design* [WWW]. Available from: <http://www.arch.usyd.edu.au> [Accessed 08/02/2005].
- GERO, J. (2000) Computational models of innovative and creative design processes. *Technological Forecasting and Social Change*, 64(2-3), pp. 183-196.
- GERO, J. (2003) Situated computing: a new paradigm for design computing. In: *CHOUTGRAJANK, A., CHAROENSLIP, E., KEATRUANGKAMALA, K., and NAKAPAN, W. (eds), CAADRIA03*, Rangsit University, Bangkok, pp. 579-587.
- GERO, J. and FUJII, H. (2000) A computational framework for concept formation for a situated design agent. *Knowledge Based Systems* 13(6), pp. 361-368.
- GERO, J. and KANNENGIESSER, U. (2004) The situated function-behavior-structure framework. *Design Studies*, 25(4), pp. 373-391.
- GERO, J. and KAZAKOV, V. (1999) Using analogy to extend the behavior state space in creative design. In: *GERO, J. S. and MAHER, M. L. (eds), Computational Models of*

Creative Design IV, Key Centre of Design Computing and Cognition, University of Sydney, Sydney, Australia, pp. 113-143.

GERO, J. and KENNENGIESSER, U. (2003) Towards a framework for agent-based product modeling. In: *International Conference on Engineering Design*, Stockholm, August 2003, paper no 1621 ICED03 FPC, CDROM, pp. 1-10.

GERO, J. and SAUNDERS, R. (2000) Constructed representations and their functions in computational models of designing. In: *B. K. Tang, M. Tan and Y. C. Wong (eds), CAADRIA2000, CASA, Singapore, pp. 215-224.*

GERO, J. and SOSA, R. (2002) Creative design situations: artificial creativity in communities of design agents. In: *proceedings of CAADRIA, 2002*. New York, Prentice Hall, pp. 191-198.

GERO, J.S. (1999) Constructive memory in design thinking. In: *GOLDSCHMIDT, G. and PORTER, W. (eds), Design Thinking Research Symposium design Representation*, Cambridge, MIT, pp. 29-35.

GERO, J.S. and KULINSKI, J.M. (2000) A situated approach to analogy in designing. In: *TANG, B-K., TAN, M., and WONG, Y-C. (eds), CAADRIA2000, CASA, Singapore, pp. 225-234.*

GIRARD, P. and ROBIN, V. (2006) Analysis of collaboration for project design management. *Computers in Industry*, 57(8-9), pp. 817-826.

GOEL, P. S., and SINGH, N., (2001). A flexible approach for prioritization in product development process. *Global Journal of Flexible System Management*, 2(1), pp.19-28.

GOMES, P., SECO, N., PEREIRA, F. C., PAIVA, P., CARREIRO, P., FERREIRA, J. L., and BENTO, C. (2006) The Importance of Retrieval in Creative Design Analogies. *Knowledge-Based Systems*, 19(7), pp. 480-488.

- HEWETT, T. T. (2005) Informing the Design of Computer-Based Environments to Support Creativity. *International Journal of Human-Computer Studies*, 63(4-5), pp. 383-409.
- HOEBEN, A., and STAPPERS, P. J. (2005) Direct Talkback in Computer Supported Tools for the Conceptual Stage of Design. *Knowledge-Based Systems*, 18(8), pp. 407-413.
- HORI, K. (1997) Concept Space Connected to Knowledge Processing for Supporting Creative Design. *Knowledge-Based Systems*, 10(1), pp. 29-35.
- HSIAO, K-A, and CHEN, L-L (2006) Fundamental dimensions of affective responses to product shapes. *International Journal of Industrial Ergonomics*, 36(6), pp. 553-564.
- HSIAO, S.W. and CHOU, J.R. (2004) A creativity-based design process for innovative product design. *International Journal of Industrial Ergonomics*, 34(5), pp. 421-443.
- HUBKA, V. (1982) *Principles of Engineering Design*. 1st English ed. London, Butterworth Scientific.
- JANSSON, D.G. and SMITH, S.M. (1991) Design fixation. *Design Studies*, 12(1), pp. 3-11.
- JOHNSON, H., and CARRUTHERS, L. (2006) Supporting Creative and Reflective Processes. *International Journal of Human-Computer Studies*, 64(10), pp. 998-1030.
- JONES, J. C. (1992) *Design Methods*. 2nd ed. New York, Van Nostrand Reinhold.
- JONSON, B. (2005) Design ideation: the conceptual sketch in the digital age. *Design Studies*, 26(6), pp. 613-624.
- KAKOTOVICH, V. (2000) Mental synthesis and creativity in design: an experimental examination. *Design Studies*, 21(5), pp. 437-449.
- KIM, M. H., KIM, Y. S., LEE, H.S., and PARK, J. A. (2007) An Underlying Cognitive Aspect of Design Creativity: Limited Commitment Mode Control Strategy. *Design Studies*, 28(6), pp. 585-604.

- KIM, M. J., and MAHER, M. L. (2008) The impact of tangible user interfaces on spatial cognition during collaborative design. *Design Studies*, 29(3), pp. 222-253.
- KOKOTOVICH, V. (2007) Problem Analysis and Thinking Tools: An Empirical Study of Non-Hierarchical Mind Mapping. *Design Studies*, 29(1), pp.49-69.
- LAWSON, B. (1984). *Cognitive strategies in architectural design*. In: N. Cross (Ed.), *Developments in design methodology*, Chichester, Wiley.
- LAWSON, B. (1997) *How designers think: the design process demystified*. Third edition. Oxford, Butterworth-Heinemann.
- LAWSON, B. (2004) Schemata, Gambits and Precedent: Some Factors in Design Expertise. *Design Studies*, 25(5), pp. 443-457.
- LEE, J., CHAE, H., KIM, C-H, and KIM, K. (2008) Design of product ontology architecture for collaborative enterprises. *Expert Systems with Applications*, doi: 10.1016/j.eswa.2007.12.042
- LEE, Y. S., HONG, S. W., SMITH-JACKSON, T. L., NUSSBAUM, M. A., and TOMIOKA, K. (2006) Systematic evaluation methodology for cell phone user interfaces. *Interacting with Computers*, 18(2), pp. 304-325.
- LEWIS, M. (2000) Aesthetic evolutionary design with data flow networks [WWW} Columbus, Ohio State University, Advanced Computing Center for the Arts and Design. Available from: <http://www.generativeart.com> [Accessed 24/05/2005]
- LI, W.D. et al (2004) Collaborative computer-aided design: research and development status. *Computer-Aided Design*, 1079(December), pp. 1-10.
- LIU, H., TANG, M. and FRAZER, H. (2004) Supporting creative design in a visual evolutionary computing environment. *Advances in Engineering Software*, 35(5), pp. 261-271.

- LIU, Y. T. (1995) Some Phenomena of Seeing Shapes in Design. *Design Studies*, 16(3), pp. 367-385.
- LIU, Y. T. (1996) Is Designing One Search or Two? A Model of Design Thinking Involving Symbolism and Connectionism. *Design Studies*, 17(4), pp. 435-449.
- LIU, Y.-C., BLIGH, T., and CHAKRABARTI, A. (2003) Towards an Ideal Approach for Concept Generation. *Design Studies*, 24(4), pp. 341-355.
- LIU, Y.T. (2000) Creativity or novelty? *Design Studies*, 21(3), pp. 261-276.
- MACMILLAN, S., STEELE, J., AUSTIN, S., KIRBY, P., and SPENCE, R. (2001) Development and Verification of a Generic Framework for Conceptual Design. *Design Studies*, 22(2), pp. 169-191.
- MCDONAGH, D., BRUEBERG, A., and HASLAM, C. (2002) Visual product evaluation: exploring users' emotional relationships with products. *Applied Ergonomics*, 33(3), pp. 231-240.
- MCGOWN, A., GREEN, G., and RODGERS, P. A. (1998) Visible Ideas: Information Patterns of Conceptual Sketch Activity. *Design Studies*, 19(4), pp. 431-453.
- MENIRU, K., RIVARD, H. and BEDARD, C. (2003) Specifications for computer-aided conceptual building design. *Design Studies*, 24(1), pp. 51-71.
- NAKAKOJI, K., YAMAMOTO, Y. and OHIRA, M. (2000) Computational support for collective creativity. *Knowledge-Based Systems*, 13(7-8), pp. 451-458.
- NAKAKOJI, K., YAMAMOTO, Y., SUZUKI, T., TAKADA, S., and GROSS, M. D. (1998) From critiquing to representational talkback: Computer support for revealing features in design. *Knowledge-Based Systems*, 11(7-8), pp. 457-468.

- OTTO, K. and WOOD, K. (2001) *Product Design Techniques in Reverse Engineering and New Product Development*. 1st ed. Upper Saddle River, New Jersey 07458, Prentice-Hall, Inc.
- OXMAN, R. (2004) Think-maps: Teaching Design Thinking in Design Education. *Design Studies*, 25(1), pp. 63-91.
- PAHL, G., and BEITZ, W. (1988) *Engineering Design: A Systematic Approach*. 1st ed. London: Design Council, Springer-Verlag.
- PARTRIDGE, D. and ROWE, J. (1994) *Computers and creativity*. Oxford, Intellect Books.
- PETRE, M. (2004) How Expert Engineering Teams Use Disciplines of Innovation. *Design Studies*. 25(5), pp. 477-493.
- PLSEK, P.E. (1996) *Working paper: models for the creative process* [WWW]. Available from: <http://www.directedcreativity.com/pages/WPModels.html> [Accessed 22/09/2005].
- PLSEK, P.E. (1997) *The tool kit: the how-to of directed creativity* [WWW]. Available from: <http://www.directedcreativity.com/pages/ToolKit.html> [Accessed 04/07/2005].
- PUGH, S. (1991) *Total Design*. 2nd ed. Wokingham, UK, Addison Wesley.
- PURCELL, A. T., and GERO, J. S. (1998) Drawings and the Design Process. *Design Studies*, 19(4), pp. 389-430.
- PURCELL, A.T. and GERO, J.S. (1996) Design and other types of fixation. *Design Studies*, 17(4), pp. 363-383.
- RASHID, A., MAC DONALD, B. J., and HASHMI, M. S. J. (2004) Evaluation of the aesthetics of products and integration of the findings in a proposed intelligent design system. In: *Proceedings of the International Conference in Advances in Materials and Processing Technologies, November 2004*. Journal of Materials Processing Technology, 153-154(2004), pp. 380-385.

- RODGERS, P. A., GREEN, G., and MCGOWN, A. (2000) Using Concept Sketches to Track Design Progress. *Design Studies*, 21 (5), pp. 451-464.
- SAUNDERS, R. and GERO, J.S. (2001a) A synthetic approach to the study of creative behavior. In: *GERO, J.S. and MAHER, M.L. (eds), Computational and Cognitive Models of Creative Design V*, Key Centre of Design Computing and Cognition, University of Sydney, Sydney, pp. 113-139.
- SAUNDERS, R. and GERO, J.S. (2001b) The digital clockwork muse: A computational model of aesthetic evolution. In: *AISB '01*, University of York, York, UK, pp. 12-21.
- SCHON, D. A., and WIGGINS, G. (1992) Kinds of Seeing and Their Functions in Designing. *Design Studies*, 13(2), pp. 135-156.
- SEDIVY, J. and JOHNSON, H. (2000) Multimodal Tool Support for Creative Tasks in the Visual Arts. *Knowledge-Based Systems*, 13(7-8), pp. 441-450.
- SEGRS, N. M., DE VRIES, B., and ACHTEN, H. H. (2005) Do Word Graphs Stimulate Design? *Design Studies*, 26(6), pp. 625-647.
- SENER, B. and WORMALD, P. (2008) User evaluation of HCI concepts for defining product form. *Design Studies*, 29(1), pp. 12-29.
- SHNEIDERMAN, B. (2000) Creating Creativity: User Interfaces for Supporting Innovation. *ACM Transactions on Computer-Human Interaction*, 7(1), pp. 114-138.
- SIMON, H. A. (1981) *The Sciences of the Artificial*. 2nd ed. Cambridge, MA, MIT Press.
- SIMON, H.A. (1988) Creativity and motivation. *New Ideas in Psychology*, 6(2), pp. 177-181.
- SMITH, G.J. and GERO, J.S. (2005) What does an artificial design agent mean by being “situated”? *Design Studies*, 26(5), pp. 535-561.

- SOSA, R. and GERO, J. (2003) Design and change: a model of situated creativity. In: BENTO, C., CARDOSA, A., and GERO, J.S. (eds). *Approaches to Creativity in Artificial Intelligence and Cognitive Science*, IJCAI03, Acapulco, pp 25-34.
- SOSA, R. and GERO, J. (2004) A computational framework for the study of creativity and innovation in design: effects of social ties. In: JS Gero (eds), *Design Computing and Cognition '04*. Dordrecht, Kluwar Academic Publishers, pp. 499-517.
- SOUFI, B. and EDMONDS, E. (1996) The cognitive basis of emergence: implications for design support. *Design Studies*, 17(4), pp. 451-463.
- SUGIYAMA, K., MISUE, K., WATANABE, I., NITTA, K., and TAKODA, Y. (1997) Emergent media environment for idea creation support. *Knowledge-Based Systems*, 10(1), pp. 51-58.
- TANG, H.H. and GERO, J. (2002) A cognitive method to measure potential creativity in designing. In: BENTO, C., CARDOSO, A. and WIGGINS, G. (eds) *Workshop 17 – Creative Systems: Approaches to Creativity in AI and Cognitive Science*, ECAI-02, Lyon, pp. 47-54.
- TANN, W., and SHAW, H-J (2007) The collaboration modeling framework for ship structural design. *Ocean Engineering*, 34(5-6), pp. 917-929.
- TERRY, M. and MYNATT, E. D. (2005) Enhancing general-purpose tools with multi-state previewing capabilities. *Knowledge-Based Systems*, 18(8), pp. 415-425.
- TOVEY, M. and OWEN, J. (2000) Sketching and direct CAD modeling in automotive design. *Design Studies*, 21(6), pp. 569-588.
- TSAI, H-C, HSIAO, S-W, and HUNG, F-K (2006) An image evaluation approach for parameter-based product form and colour design. *Computer-Aided Design*, 38(2), pp. 157-171.

- TSENG, C.J. ABDALLAH, H. (2004) A human-computer system for collaborative design (HCSCD). *Journal of Materials Processing Technology*, 155-156(2), pp. 1964-1971.
- TSENG, K.C. (2005) *A human-centered system for collaborative product development*. Unpublished thesis (PhD), De Montfort University.
- VAN DER LUGT, R. (2000) Developing a graphic tool for creative problem solving in design groups. *Design Studies*, 21(5), pp. 505-522.
- VAN DER LUGT, R. (2005) How sketching can affect the idea generation process in design group meetings. *Design Studies*, 26(2), pp. 101-122.
- VAN DIJK CASPER, G.C. (1995) New insights in computer-aided concept design. *Design Studies*, 16(1), pp. 62-80.
- VAN ELSAS, P.A. and VERGEST, J.S.M. (1998) New functionality for computer-aided conceptual design: the displacement feature. *Design Studies*, 19(1), pp. 81-102.
- VERSTIJNEN, I.M. et al. (1998) Sketching and creative discovery. *Design Studies*, 19(4), pp. 519-546.
- VISSER, W. (1996) Two Functions of Analogical Reasoning in Design: a Cognitive-Psychology Approach. *Design Studies*, 17(4), pp. 417-434.
- WARD, T. B., FINKE, R. A., and SMITH, S. M. (1995) *Creativity and the Mind. Discovering the Genius Within*. London; New York, Plenum Press.
- WON, P.H. (2001) The comparison between visual thinking using computer and conventional media in the concept generation stages of design. *Automation in Construction*, 10(3), pp. 319-325.
- YAMAMOTO, Y. and NAKAKOJI, K. (2005) Interaction design of tools for fostering creativity in the early stages of information design. *International Journal of Human-Computer Studies*, 63(4-5), pp. 513-535.

YIN, Y., VANIDES, J., RUIZ-PREMO, M. A., AYALA, C.C. and SHAVELSON, R. J. (2005) Comparison of Two Concept-Mapping Techniques: Implications for Scoring, Interpretation, and Use. *Journal of Research in Science Teaching*, 42(2), pp. 166-184.

ZHA, X. F., and DU, H. (2006) Knowledge-intensive collaborative design modeling and support Part I: Review, distributed models and framework. *Computers in Industry*, 57(1), pp. 39-55.

ZHA, X. F., and DU, H. (2006) Knowledge-intensive collaborative design modeling and support Part II: System implementation and application. *Computers in Industry*, 57(1), pp. 56-71.

ZIZ-AV, A. and REICH, Y. (2005) SOS subjective objective system for generating optimal product concepts. *Design Studies*, 26(5), pp. 509-533.

APPENDIX A

PUBLISHED WORKS FROM THIS RESEARCH

1. SALAH, F. and ABDALLAH, H. (2008) Creative Design Tools (CDT): Stimulating creative design thinking. *International Journal of Design Engineering (IJDE)*, Accepted for publication.
2. SALAH, F. and ABDALLA, H. (2008) A knowledge-Based system for enhancing creative design. *International Journal of Computer Applications in Technology (IJCAT)*. Submitted.

Creative Design Tools (CDT): Stimulating creative design thinking

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Abstract: This research paper presents a knowledge-based system for creative design tools (CDT). The developed system provides designers with a creative design environment to enhance their design thinking. Several creative thinking tools and techniques are grouped, developed, and incorporated with various constructive knowledge databases which can widen the designer's knowledge and search skills in the process of design creation. CDT embodies: a user interface, five design modules, creativity tools, knowledge databases, and a computer-aided design (CAD) tool. The main aim of the system is to enhance creative design thinking by providing various tools and constructive knowledge databases which can be expanded each time the designer uses the system. The system differs from conventional tools in that it is structured to incorporate creativity tools with knowledge databases needed by the designers in a user friendly environment. A case study is discussed and demonstrated to validate the proposed system.

Keywords: Creative design, conceptual design, computer supported design, creative design tools, design computation, interdisciplinary, knowledge-based systems, product design, spatial design, complexity in design, collaborative design.

Reference to this paper should be made as follows: Salah, F., and Abdalla, H. (2008) 'Creative Design Tools (CDT): Stimulating creative design thinking', *Int. J. Design Engineering*, Vol. *, No. *, pp. *-*.

Biographical notes: Feda Salah is currently pursuing her PhD in Product and Spatial Design Department at De Montfort University, Leicester in the UK. She received her Masters Degree from Industrial Engineering Department of University of Jordan in 1995. She worked as a lecturer at Philadelphia University from February 2000 to September 2004. Her current research areas include creative design, collaboration, design computation and web/internet-based engineering.

Professor Hassan Abdalla is currently the Head of Product and Spatial Design Department at De Montfort University in the UK and a leading authority in the field of rapid and sustainable product development, concurrent engineering, and design for assembly/disassembly. He is the founder of the rapid product development research group at De Montfort University Leicester which has a high reputation, both on a national and an international level. It has very strong links with a number of organisations and institutions world-wide. For a number of years Professor Abdalla worked in industry before joining academia. He is the author/co-author of more than 80 research papers published in international journals and refereed conferences. He has been invited as a keynote speaker for several conferences and

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currently serving on the technical reviewing committees of a number of journals. Professor Abdalla has led several national and international funded projects, from both the Commission of the European Union and EPSRC.

1. Introduction

Creativity is considered to be a mysterious phenomenon. It can be defined as coming up with new, unique, and novel ideas. Two different debates were addressed: one considers creativity as a conditioned and inherited behaviour, a talent that only special people can have, while the second considers that every one exhibits analytical, distinct, and pioneer talent to some extent. The main aim of this research is to develop the second concept of creativity by defining the techniques and providing the proper tools to enhance creative thinking and become more competitive in the future consumer market. This also involves getting familiar with how creativity works and how it is evaluated, when and where.

All previous research studies discussed specific areas but lacked the holistic view of design systems necessary to support design teams throughout the design process. Design is considered a goal-oriented, problem-solving activity that relies on many several factors, namely human experience, creative thinking and related knowledge. These three key elements should be integrated within any design development and accompanied by suitable design methodologies made possible by advancements in computer technologies and design computation in order to achieve the most creative and competitive results.

The main objective of this research is to investigate and develop a human computational creative environment for design thinking by combining appropriate creative tools with appropriate knowledge. Creativity can be achieved at any level of the design process therefore, it is necessary to consider design processes from the preparation stage to the detailed design stage. The proposed research has therefore involved addressing the issue of creative thinking in design from a holistic perspective in addition to establishing a new approach for applying evolutionary computing and visualizing technology to support creative design thinking. The contribution to previous work in the area is the proposed holistic framework combining several creativity tools for enhancing designers' thinking and use of appropriate databases for design tasks, especially CAD tools, and design modules. Using this integrated holistic framework the designer can start by formulating the problem and stimulating his creative thinking throughout the whole design process. The proposed architecture was formulated through investigation of design protocols, cognition and creativity, design computation techniques, visual design tools, creative tools, in addition to product design and development methods. All this, combined with the analysis of other challenges facing designers, provided a solid base for the proposed architecture.

2. Literature Review

Design is considered a complex and sophisticated skill which must be learnt like any other skill (Lawson, 1997). Learning design skills relies on controlled practice and the development of proper techniques and methods. Design methods are classified into two major groups; *creative methods* which act by increasing the flow of ideas, removing the mental blocks that inhibit creativity, and widening the search area, *rational methods* which encourage a systematic approach to design (Cross, 2000). Design, as a goal oriented, constrained, decision making, exploration and learning activity, operates within a situation related to the designer's perception of a situation which produces a description of a future engineering design (Gero, 2000).

Several factors were found to affect design thinking among designers such as human cognitive processes (Kim et al., 2007), strategies used (Pereira and Cardoso, 2006), design processes followed (Johnson and Carruthers, 2006), domain knowledge, and experience (Lawson, 2004). Visual perception is essential in design thinking. Applying knowledge to design situations is always based on the way designers interpret what they see through pre-attentive, and attentive visual processing (Baxter, 2002). Computers proved to stimulate the generation of ideas strongly and more frequently based on immediate visual feedback (Won, 2001). Furthermore, the use of annotations or word graphs in design proved to improve work flow with more associations (Segers et al., 2005). Some cases of fixation in design were recognized in situations associated with absence of domain specific knowledge and reliance on everyday knowledge (Jansson and Smith, 1991; Purcell and Gero, 1996). On the other hand, the importance of reasoning was addressed as an important feature of human intelligence that proved to enhance design thinking and produce novel designs (Visser, 1996; Chakrabarti and Bligh, 2001; Gomes, et al, 2006).

Engineering design process involves the establishment of requirements based on human needs, followed by transformation of those needs into specifications and functions, which in turn are mapped and converted into design solutions using creativity, scientific principles and technical knowledge to be cost-effectively manufactured (Bruce and Cooper, 2000; Liu, et al., 2004; Darlington and Culley, 2004; Ziz-Av and Reich, 2005; and Lin et al., 2008). Conceptual design is one of the early stages in the design process that demands the greatest creativity. Its main aim is to produce design principles concerning the product form and function to satisfy customers' requirements and be competent. Many concepts are usually generated at this stage, followed by the selection of the best promising alternatives (Baxter, 2002). Therefore emphasis on this design stage, with the proper tools and techniques, can enhance the creative design thinking tremendously. A divergence-convergence approach have been presented and discussed by several researchers, (Cross, 1997; Liu et al., 2003; Ward, 2007). Generation of concepts is a divergent step while the evaluation and selection of concepts is convergent.

Drawing is believed to be a way of externalising the designer's thoughts and ideas through the various design processes. Sketches and diagrams are mainly used in the early design stages of concept generation. Sketching was recognized as important to stimulation of creative design thinking as well as visual perception in conceptual design (Verstijnen et al., 1998). It provides new directions for idea generation through representational talkback, facilitates better access to earlier ideas, and exchange of ideas among designers (Rodgers et al., 2000; Hoeben and Stappers, 2005; Van Der Lugt, 2005). On the other hand, the impact of digital technology on conceptual tools and sketching has been investigated (Jonson, 2005; Kara et al., 2007; Huang, 2008). Therefore, it is the interaction among visualization and tools that support the design concept generation.

Two broad definitions of creativity have been reviewed: one promotes that creativity can be solely a mental phenomenon (P-creativity) psychological creativity; the other recognises that creativity goes beyond the generation of novel ideas since society plays an important role in defining what is creative (H-creativity) historical creativity (Gardner, 1994; Boden, 1994; 2007). Few creativity models in design have been developed to assist designers. (Simon, 1988) proposed a creative design model at the individual level; while (Csikszentmihalyi, 1996) developed the social-cultural creativity system to identify sources of creativity, rather than what creativity is. (Liu, 2000) combined these existing models of creativity and came up with the dual generate-and-test model. It encapsulates two generate-and-test loops; one at the level of the individual, and the other at the level of society. Creativity can be found in the interaction among these elements. (Tang and Gero, 2002) introduced a new level under the individual area in

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Csikszentmihalyi's system, namely the design process. Several descriptive models of creative design were discussed including combination, mutation, analogy, first principles and emergence (Cross, 1997; Liu et al., 2004, and Gu et al., 2006). Several other research works discussed creative graphical tools including visual and classic brainstorming (Van Der Lugt, 2000). Some others discussed concept mapping (Abdalla and Anderson, 2001; Anderson, 2002; Oxman, 2004; Yin, et al, 2005; Kokotovitch, 2007). Hence the occurrence of a creative idea, object, or action is determined jointly by the relationship among the individual, society, culture, and the process in conjunction with the tools used.

Some computational creative models to support design and product development have been developed (Gero, 2003; Gero and Kannengiesser, 2004; Ye, et al., 2007). Creativity is a human feature; therefore, it is not easily converted into a computational tool (Liu et al., 2004). It was recognized that computational tools do not stimulate creativity but, rather, stimulate the designer to catch sudden inspiration by exploring innovative designs more easily. Design computation was recognized to provide flexible and usable support which complements the designer thinking processes, and achieve fluent interaction between designers and knowledge they require with several channels of exploration open in parallel (Candy and Edmonds, 1996; 1997).

Collaboration was recognized to support the design process by minimizing the lead time of the product development through sharing of information and resources between individuals and organisations. Several researchers indicated the benefits of collaboration through the different design processes (Tseng and Abdalla, 2004; Tseng, 2005, and Mok et al., 2008). Two collaboration modes were addressed: a horizontal and a hierarchical mode. These collaboration modes are complementary in functions. They established a vertical linkage between the design and the manufacturing processes, and a horizontal linkage of team work in the design phases (Li et al., 2005).

The literature survey has established that design is a learnt skill which can be enhanced by use of appropriate concepts, methods, and tools to explore more creative ideas in the design space. Furthermore, it stresses the important role of design computation as a great potential for developing future creative design systems to support design teams and minimize the product lead time starting from the early phases of design. Several of the identified frameworks for creative design were focussing upon a specific tool or approach and lacked the holistic approach to the problem. The need for such a holistic approach to enhance creative design thinking by providing an integrated flexible design environment with the proper knowledge, processes, and creative tools proved to be a necessity and since design is a nonlinear process a concurrent design platform will be useful in such systems.

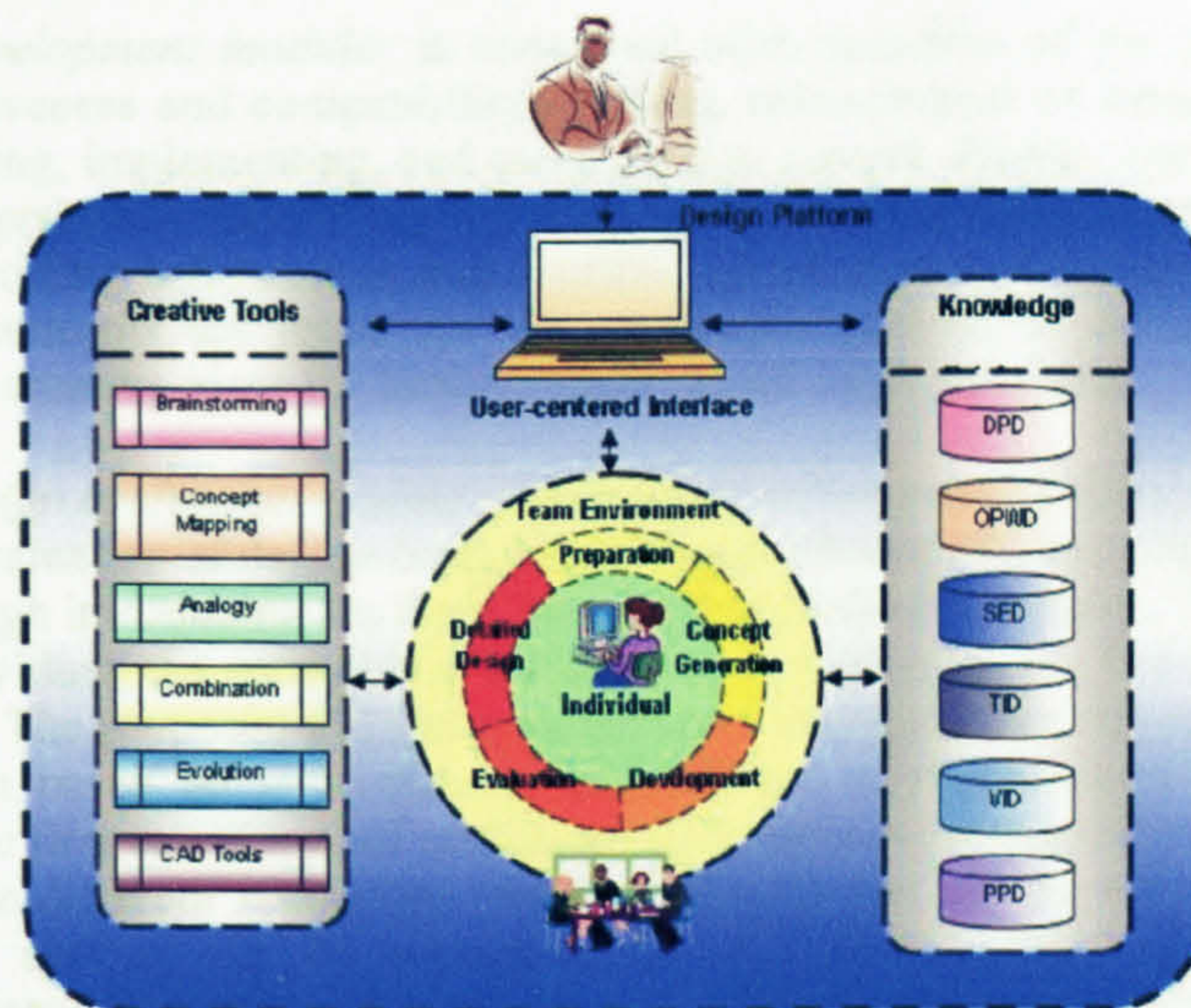
To overcome the shortcomings of the existing models described in the literature, a comprehensive and flexible Creative Design Tools (CDT) system is proposed. This system provides the design team with the required design knowledge, creative design tools, design processes, and the individual and team design environments within a concurrent flexible design platform. The design team is the main core of the system which is meant to support the team rather than seeking to automate the design process.

3. The developed system model

Some of the tools available do help designers to brainstorm and present their ideas visually, while others provide more options based on existing alternatives using a certain parameter or method which can extend the range of alternatives to be developed and evaluated. To obtain the most creative results from design, creative tools should be used in conjunction with knowledge capture and a preferred design process. The proposed Creative Design Tools CDT model integrated those components within a flexible,

individual, and team design environment which encompasses a user interface, five design modules, creative design tools, and knowledge databases. The overall architecture of the CDT system is shown in Figure (1). Detailed descriptions of each component in the proposed framework are given in the following sections.

Figure (1) Proposed generic framework



3.1 Design modules

The proposed CDT system is composed of five major modules for a systematic design process, each of which services several of the processes conducted by the design team, and the different tools assisting the design process. Although the design process is non-linear as already acknowledged in the framework, the following description of the design process takes a linear approach for the purpose of explanation.

3.1.1 The preparation module: services the first step in the design process. It consists of a range of tasks designed to provide the designer with a solid background, and to guide his design process. The client's needs, objectives, requirements, constraints, and cultural influences are comprehensively established through discussions and interviews. Building on that information; problem formulation is clarified for the designers. Searching for related information and its analysis can provide designers with the basis for reformulating the problem and amending the design requirements, brief, and constraints. The design team, by this means, formulates a comprehensive understanding of the design problem and is able to proceed with use of the concept generation module.

3.1.2 The concept generation module: constitutes a major part of the whole system, for it encompasses the use of the different creative thinking tools to explore more creative and novel concepts. The concept generation process is divided into two main stages; the first is the preliminary stage which starts with brainstorming ideas and using concept maps and analogy to present the proposed alternatives either individually or as teams. The supplementary stage can be started, after the preliminary designs are produced, by using combination, and evolution tools based on the created concepts, or any existing concepts in some other domains. Results are displayed for designers to choose

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appropriate design alternatives for further development. The incorporated tools in the concept generation module of the CDT system facilitate the creation of more options in the solution space to select from. This generation and exploration of a wide range of concepts helps in minimising design fixation through widening the search solution space for designers by providing more various options to choose from. This in turn can trigger some hidden ideas and helps designers to externalize more design solutions.

3.1.3 The development module: is concerned with selection of the suitable options based on attractiveness and compatibility of ideas, enhancement of ideas using a check list such as shaping, implementing, and comparing to current. Finally, the developed idea is documented precisely identifying its benefits, positive points, negatives, potential downsides, supporting information, and intuitive conclusion. Following these processes the developed concepts are ready for the evaluation process to decide on the most satisfactory, and creative ideas for further detailing and implementation.

3.1.4 The design evaluation module: presents one of the most challenging processes to structure. The evaluation of design concepts has been achieved by developing the work of Liu (2000) through introducing the three inter-related evaluation modes. The first is at the level of the individual, the second is at the level of the design team, and the last is at the level of society. The proposed CDT system achieves evaluation at the level of individual and design team based on multi-dimensional criteria; appropriateness and novelty. If concepts pass the first two stages of evaluation they are transferred to the final evaluation by society where different specialties and backgrounds are involved. Evaluation, in the proposed CDT system can be conducted at any design stage starting from the brainstorming ideas. Therefore, abstract ideas are evaluated as well as detailed ones. This approach can help in minimizing the lead time for new designs to be created by eliminating the inappropriate ideas from the early stages without wasting so much time on developing useless ones.

3.1.5 Detailed design module: is the phase where the selected developed designs are dealt with in full details. At this stage several additional processes take place namely: definition of specifications, production of working drawings, and 3D modelling.

3.2 Creative design tools

The proposed (CDT) system incorporates some of the wide choice of available creative tools. Research showed that these tools are very useful for design tasks in specific domains. Each tool has its own ways of supporting the design team in their tasks. The suggested tools for use within the system are brainstorming, concept mapping, analogy, combination, and evolution in addition to CAD.

3.2.1. Brainstorming: is a common tool for creative thinking to generate a large number of ideas. Several ways of brainstorming are available using either words or graphical presentations. A combination of graphical and verbal presentations is adopted. The system provides the designer with two options, either building his own samples using existing items and components, or sketching from scratch using CAD tools. Brainstorming usually takes place over a prescribed period and with short tasks to be achieved by the end of each session. The generated ideas are stored temporarily in the database for further development and evaluation.

3.2.2 Concept Mapping: is a very useful tool in design concept generation as discussed in the literature. It is a tool to help designers focus thinking which is crucially

important and re-structure their own ideas in a more systematic way and thereby enhance their creative thinking. The concept mapping tool in the proposed CDT system is designed to organize design alternatives in a hierarchical tree structure which is comprehended by the designer and realized by the creative tools computation processes. These structures are stored in the databases immediately and can be retrieved and amended through the design task in hand. The function of this tool is to stimulate creative ideas, store them, and link to other maps, CAD models and databases. Any CAD tools can be used to sketch the ideas in parallel with the brainstorming and use of the concept mapping tools.

3.2.3 Analogy: involves the transfer of prior knowledge from a familiar existing situation (source) to a new revealed situation (target). This requires a source space, a target space, and a modified space as illustrated by (Gero 2000) and presented in the following procedures:

- Matching and retrieval: in this step the artefact with the highest similarity is retrieved for further processing.

$$\text{SIM} (D_T, D_S (i)) = \max_k \text{SIM} (D_T, D_S (k)) \quad (1)$$

where $\text{SIM} (*,*)$ is a real function which measures the degree of similarity between its parameter spaces.

$D_S (i)$ is the i -th source design state space

D_T is the target design state space.

- Mapping and transformation: in this step mapping adds some design variables from the i -th source design state space to the target design state space and then transforms the result of this operation into a modified design space D^m .

$$D^m = \tau (D_T \cup M (D_S (i))) \quad (2)$$

where M is a mapping operation

τ is a transformation operator.

The previously presented procedures of matching and retrieval, and mapping are developed and more specified in the proposed CDT system by using various analogical parameters. Since the developed CDT system used the function, behaviour, and structure design representation, these identified features are used as the analogical parameters for matching and retrieval and as a base for mapping.

Matching and retrieval in the proposed system is conducted by using one or more of the identified functions, behaviours, or structures as a parameter for similarity search in order to match and retrieve design options. This procedure has many advantages over Gero's procedure. At first it provides flexibility for designers to decide on the parameter type because the parameters are identified by designers and chosen by them. Second the solution space can be minimized or enlarged according to the used parameter which means the designers can release the constraints or tighten them according to their preference. Furthermore, retrieval time is minimised because the search is accomplished at a certain division in the database which is identified by the chosen parameter. The proposed matching and retrieval alternative procedures are detailed as follows:

$$\text{SIM} (Fn_T, Fn_S (i)) = \max_k \text{SIM} (Fn_T, Fn_S (k)) \quad (3)$$

$$\text{SIM} (B_T, B_S (i)) = \max_k \text{SIM} (B_T, B_S (k)) \quad (4)$$

$$\text{SIM} (S_T, S_S (i)) = \max_k \text{SIM} (S_T, S_S (k)) \quad (5)$$

$$\text{SIM} [(Fn_T, Fn_S (i)) \cup (B_T, B_S (i))] = \max_k \text{SIM} [(Fn_T, Fn_S (k)) \cup (B_T, B_S (k))] \quad (6)$$

$$\text{SIM} [(Fn_T, Fn_S (i)) \cup (S_T, S_S (i))] = \max_k \text{SIM} [(Fn_T, Fn_S (k)) \cup (S_T, S_S (k))] \quad (7)$$

$$\text{SIM} [(B_T, B_S (i)) \cup (S_T, S_S (i))] = \max_k \text{SIM} [(B_T, B_S (k)) \cup (S_T, S_S (k))] \quad (8)$$

$$\text{SIM} [(Fn_T, Fn_S (i)) \cup (B_T, B_S (i)) \cup (S_T, S_S (i))] = \max_k \text{SIM} [(Fn_T, Fn_S (k)) \cup (B_T, B_S (k)) \cup (S_T, S_S (k))] \quad (9)$$

where Fn_T is the target function space

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$F_{n_s}(i)$ is the i -th source function space
 B_T is the target behaviour space
 $B_s(i)$ is the i -th source behaviour space
 S_T is the target structure space
 $S_s(i)$ is the i -th source structure space

Mapping recommences using the chosen concepts. It can be structural-based, functional-based and/or behavioral based. It is conducted at the level of the features values where these values are either combined or substituted. The proposed mapping procedures are detailed as follows:

$$D^m = F_n^m \cup B^m \cup S^m \quad (10)$$

$$F_n^m = \tau (F_{n_T} \cup M (F_{n_s}(i))) \quad (11)$$

$$B^m = \tau (B_T \cup M (B_s(i))) \quad (12)$$

$$S^m = \tau (S_T \cup M (S_s(i))) \quad (13)$$

where D^m is the modified design space
 F_n^m is the modified function space
 B^m is the modified behaviour space
 S^m is the modified structure space

3.2.4 Combination: is built on combining two or more different samples, components, or items to come up with a new one, or to combine two or more different features' values to create a new one. When computerized, this tool can provide designers with more combination alternatives which might trigger a hidden creative idea. This technique can be achieved on a structural, functional, and behavioural level. Four types of combination are identified and included in the proposed CDT system: systematic combination, tree random combination, vertices random combination, and total random combination. The four types are illustrated in detail in the following:

- *Systematic Combination*

$$\begin{matrix} n & k \\ \{ \{ u_{ij} \} \} \end{matrix} \quad (14)$$

where n = number of vertices in each tree
 k = number of trees

- *Tree Random Combination*

$$\begin{matrix} n & k \\ \{ \{ v_{g(i)j} \} \} \end{matrix} \quad (15)$$

where g is a permutation on $\{1, 2, 3, \dots, k\}$
 ** (choosing the trees randomly)

- *Vertices Random Combination*

$$\begin{matrix} n & k \\ \{ \{ v_{if(j)} \} \} \end{matrix} \quad (16)$$

where f is a permutation on $\{1, 2, 3, \dots, n\}$
 ** (choosing the vertices randomly)

- *Total Random Combination*

$$\begin{matrix} n & k \\ \{ \{ v_{g(i)f(j)} \} \} \end{matrix} \quad (17)$$

where g is a permutation on $\{1, 2, 3, \dots, k\}$
 f is a permutation on $\{1, 2, 3, \dots, n\}$
 ** (choosing the trees and vertices randomly)

3.2.5 Evolution: has been used as an optimiser in most cases, and as an explorer in recent cases concerning conceptual designs. The second option is adopted in the CDT system. This tool involves two main processes, namely cross over and mutation. The evolutionary framework includes an evolutionary algorithm, genotype representation, embryogeny, phenotype representation, and a fitness function (in this case processing of user input).

- Cross over is the crossing between parts of the tree from two or more parents. In the proposed CDT system crossing over is achieved between structural nodes, functional nodes, or behavioral nodes. it is modeled as follows:

$$S_{new1} = [S_{parent1} - \hat{S}_{parent1}] \cup \hat{S}_{parent2} \quad (18)$$

$$S_{new2} = [S_{parent2} - \hat{S}_{parent2}] \cup \hat{S}_{parent1} \quad (19)$$

$$Fn_{new1} = [Fn_{parent1} - \hat{Fn}_{parent1}] \cup \hat{Fn}_{parent2} \quad (20)$$

$$Fn_{new2} = [Fn_{parent2} - \hat{Fn}_{parent2}] \cup \hat{Fn}_{parent1} \quad (21)$$

$$Bh_{new1} = [Bh_{parent1} - \hat{Bh}_{parent1}] \cup \hat{Bh}_{parent2} \quad (22)$$

$$Bh_{new2} = [Bh_{parent2} - \hat{Bh}_{parent2}] \cup \hat{Bh}_{parent1} \quad (23)$$

where \hat{S} is part of the structure

S is the whole structure

\hat{Fn} is part of the function

Fn is all the functions

\hat{Bh} is part of the behavior

Bh is all the behaviors

- Transformation (Mutation) is the alteration of one or more feature variables by an external process. In the proposed CDT system it is modeled as:

$$Fn_{new} = \Phi_m(Fn_{existing}) \quad (24)$$

$$B_{new} = \Phi_m(B_{existing}) \quad (25)$$

$$S_{new} = \Phi_m(S_{existing}) \quad (26)$$

where Φ_m is a transformation operator

Fn is the function of an object

B is the behaviour of an object

S is the structure of an object

Using the knowledge representations described earlier this tool can be applied to any design knowledge available in any design process.

3.3 Object-oriented knowledge databases

It is very important that the designers should be provided with appropriate knowledge for each design task before starting the design process. The system encompasses several constructive databases which can provide various data necessary for the design task. The more the design teams become experienced the more expert their databases will become. The databases provided can vary depending on the type of design problem either product, spatial or other design field. Six knowledge databases are proposed and explained in the following sections.

- **Design Problem Database (DPD):** contains necessary information about the design problem, including clients, projects, requirements, concepts and designers. It is a temporary database used until the design problem is solved. The final design project is transferred to the Previous Projects Database (PPD) after the project is finished. The design team can keep referring to this database as necessary. It is built by the designers themselves based on meeting with clients, searches and concept generation.
- **Other Designers Work (OPWD):** contains other designers' work. This is where the design team can expand their vision and scope of the design state space to get

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inspiration, or open up new areas for exploration. Creative design tools use this database as a source domain where good options can be found and mapped for further processing.

- *Technical Information Database (TID)*: contains technical information the design team might need to provide them with the latest state of the art technologies and techniques for any particular design problem that they are dealing with. This database can be updated at anytime and is expanded each time the designer adds new useful data explored in a new design.
- *Visual Images Database (VID)*: contains images from any appropriate source. These images may originate in nature, cultural sources, products; they may be of man-made materials or designs. The images have the same constructive representation used by the CDT system to be easily retrieved and mapped to any other target design.
- *Search Engine Database (SED)*: connects designers with internet sources to conduct their own search in any field they choose. The search results will be held in this database until the whole process ends. Afterwards the necessary information will be sent to the relevant databases for reference in future work.
- *Previous Projects Database (PPD)*: contains previous projects undertaken by the design team. Once a design problem has been solved, it is stored in this database as a reference for amendments or for designers in future work. It includes information about the functional, structural, and behavioural aspects of each design project.

3.4 *User-centred Interface*

The proposed CDT system interface provides the users with the most creative, flexible, and easy to handle menus, and tools to facilitate the design process to save time and effort. The interface comprises of windows, menus, various images such as tree views, buttons, text, transcripts, bitmaps, drop down lists, and data grids. The result is a user friendly interface to navigate through the CDT system easily, free of restrictions, and with the possibility of customizing it to the user's needs. The shell tool upon which the interface is based provides a wide range of options for designing interfaces to support creativity and achieve the best results.

3.5 *Individual and team design environments*

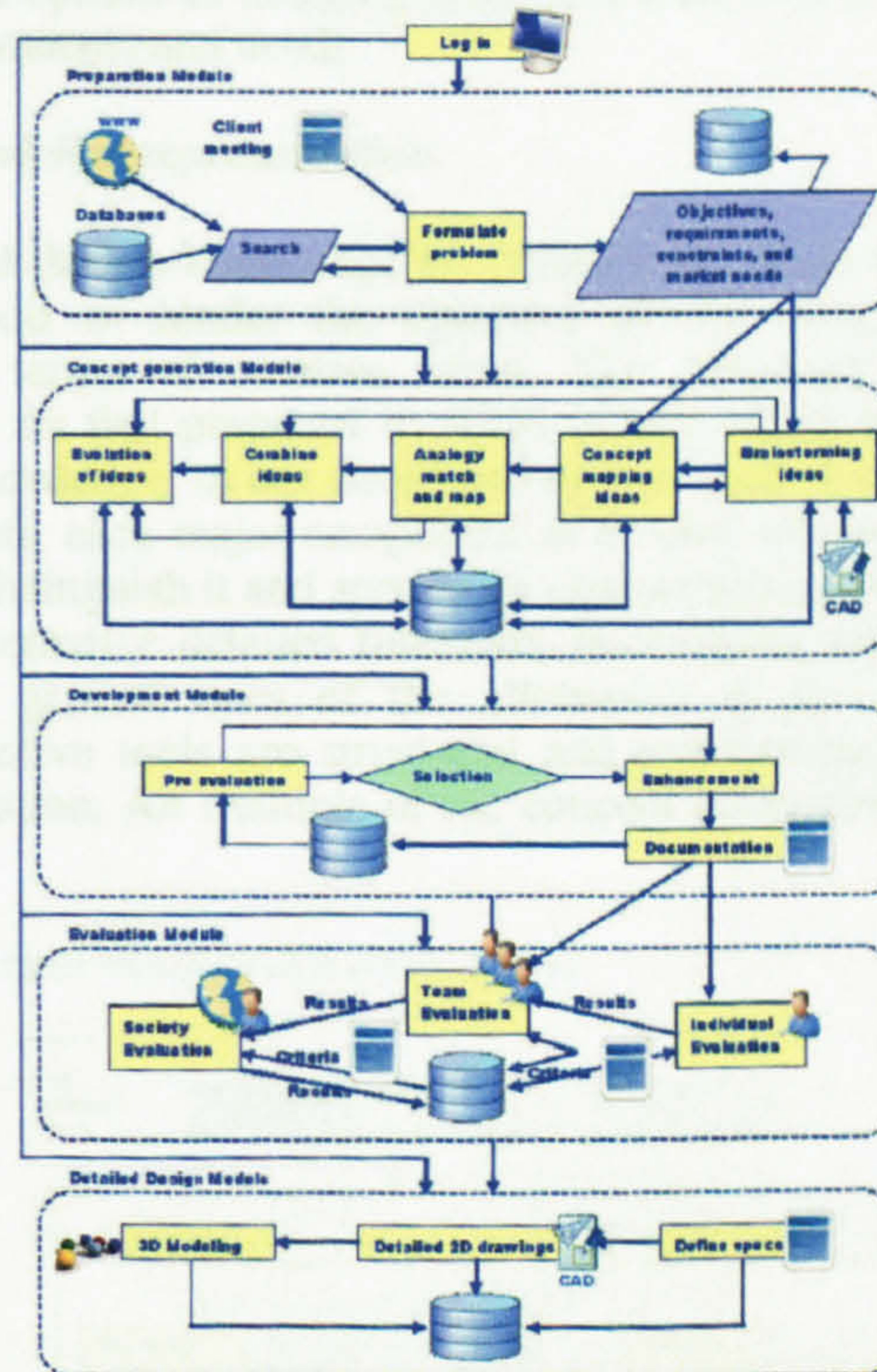
The system provides each designer with his own design environment where he can explore the different parts of the system and work through the various modules. Each designer can personalize his working environment by changing the features of the user-centred interface according to his own preference. The system also provides team design environment to be used by design teams at certain stages of the design process. The two environments, i.e. the individual and the team, are interrelated to achieve more cooperation and collaboration between the two. The system can be integrated with CAD tools to provide the designer with flexible sketching media at any stage of the design process.

3.6 *System scenario*

The CDT system scenario, as shown in Figure (2), starts by defining the design problem requirements (problem formulation) through meeting with clients and relevant searches. These requirements can be amended at any time during the design process according to any results found or concepts generated (problem reformulation). The brainstorming mode and concept mapping are used in conjunction with CAD tools to produce design

alternatives. These tools can be used by individual or team designers. The hierarchical structure of the concept mapping tool maps the design features to the object oriented structure of samples where they will be used by other tools in later stages. At this point analogy, combination, and evolution are used. Analogy matches and retrieves various ideas based on the analogical parameter chosen by the designer; functional, behavioural, and/or structural. The system displays the results of matching and retrieving to the user to aid selection from the options. The system provides the designer with various options for mapping; substituting, combining, or transferring.

Figure (2) CDT scenario



Combination can be applied to the concepts generated initially, analogical generated concepts, or a combination of both newly generated concepts and those stored in the provided databases. The designer may decide on the relevant combination. Four different types of combinations are provided: systematic combination, tree random combination, vertices random combination and total random combination. The designer is able to choose the combination method to use and select from the displayed results the most creative options according to his individual evaluation.

The Evolution tool requires identifying two parents to start the evolutionary process of cross over and mutation to provide more children from the provided parents. The designer chooses the parent options to start from and selects the most suitable created options at the end of evolutionary iteration to feed the tool with new parent options to conduct more generations.

After achieving a good resource of concept alternatives, development of these options begins. Concept alternatives are evaluated by the individual designer according to

the provided evaluation criteria, then team evaluation takes place and the results are added to the individual one. Finally, society evaluation takes place. This is where the results are displayed again to the team to reach a final decision based on the accumulated evaluation results achieved. The chosen concepts are then finalised and detailed.

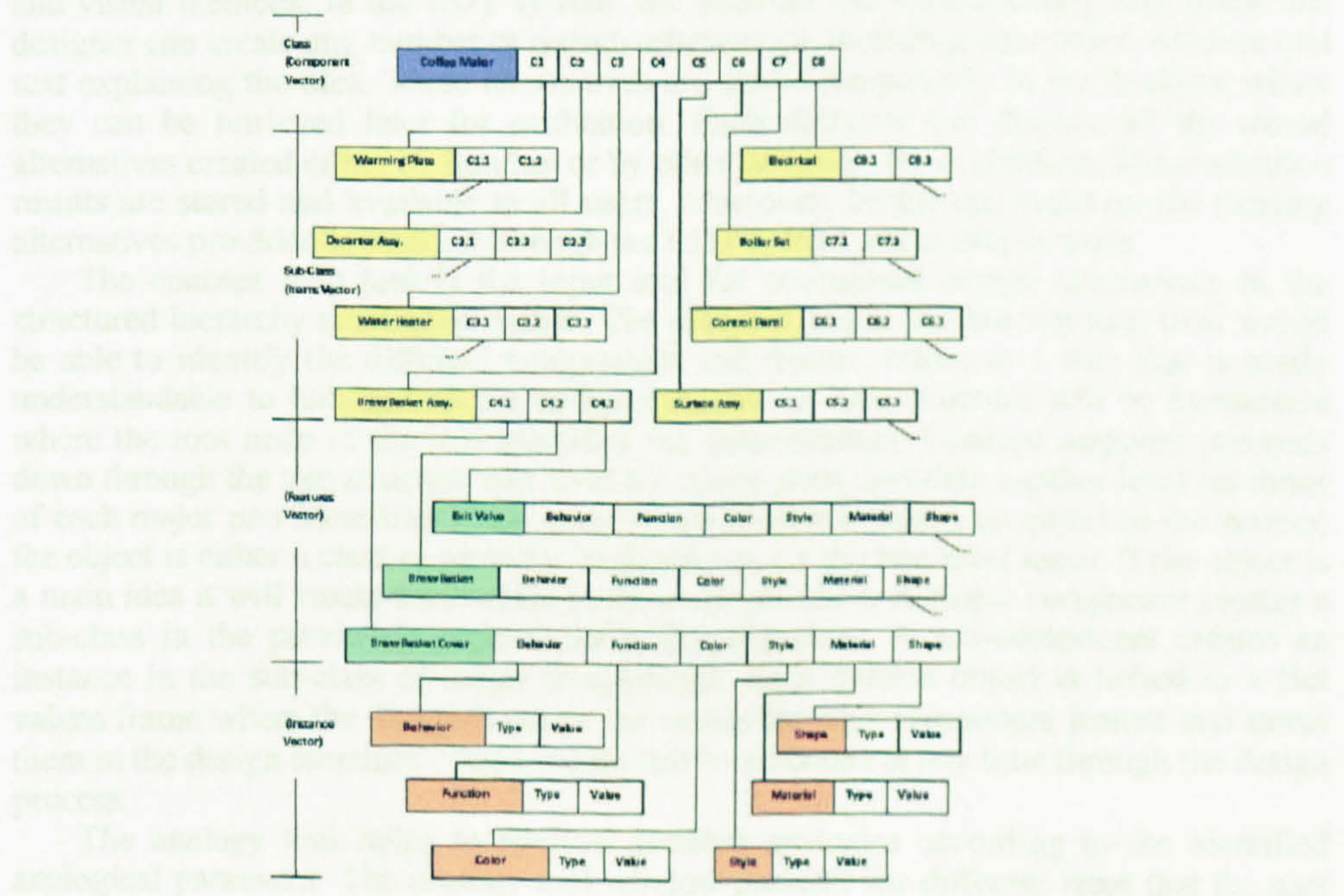
4. System implementation

The prototype system is developed with certain aspects of a well-engineered design system in mind, taking into consideration efficiency, maintainability, reliability and the needs of a creativity support design environment. The system is designed to provide the user with flexible options of design processes and creative design tools according to each designer's requirements and needs.

4.1 Design knowledge representation

Representation of design knowledge is a major concern in implementing (CDT) system for it can support or hinder the objective of the design system to increase their productivity in terms of creative ideas. The proposed design representation was developed based on that proposed by Gero (1990) which includes function, behaviour, structure, and knowledge. In our developed system each design alternative is divided into major components, each major component is divided into items with different identified features which distinguish it and specify its characteristics. For each component and item in the design alternative detailed functions, behaviours, and structures are identified in addition to the general ones of the alternative in this hierarchical structure. The incorporated creative tools are structured and implemented based on this hierarchical design representation. An example of the concept alternative representation is shown in Figure (3).

Figure (3) Hierarchical structure of a coffee maker



Features are structured to include structural, behavioural, and functional data. Relationships between different parts of the designed sample are identified using objects tree hierarchical structure and methods embedded within each object. The data identified in those representations are stored in the databases and can be retrieved and used by all the incorporated creative tools. Figure (4) shows a sample data definition window.

Figure (4) Product structures definitions

Product No	Product Description
Select 1	Corded telephones
Select 2	Cordless telephones
Select 3	Coffee makers
Select 4	Wireless baby monitors

Structure Category	Structure Product Code	Structure Product	Description
Choose Style	1	Modern	fine lines, abstract designs
Choose ColourTheme	7	Light	white, silver, transparent
Choose Size	4	large	4-8 cups
Choose Material	1	Natural	recyclable material

Item:

Structure Category:

Structure Item:

Structure Item Description:

Buttons: ADD, DELETE, UPDATE

4.2 Tools representation

The Brainstorming tool is used to display the designer's personal design ideas in a more comprehensible way that is easier to communicate, discuss and store. Combination of text and visual methods, in the CDT system, are used for the brainstorming tool where the designer can create any number of design alternatives, including alternative sketches and text explaining the idea. These alternatives are stored temporarily in the database where they can be retrieved later for evaluation. Each designer can display all the stored alternatives created either by him/her or by other designers for evaluation. The evaluation results are stored and available to all users. Moreover, he/she can build on the existing alternatives provided to him/her through the CDT system and available tools.

The concept map tool is the input tool for conceptual design alternatives in the structured hierarchy mentioned earlier. The designer, using the concept map tool, would be able to identify the different components and feature values in a way that is easily understandable to him and to the embedded tools. A tree structure will be formulated where the root node of the tree identifies the main product. Concept mapping proceeds down through the tree structure one level for major parts, and then another level for items of each major part identified. Each input by the designer creates an object in the system; the object is either a class or an instance depending on the tree level input. If the object is a main idea it will create a sub-class in the concepts class. A major component creates a sub-class in the previously created main idea sub-class. A sub-component creates an instance in the sub-class of major components. Each created object is linked to a slot values frame where the designer enters the values for each component feature and stores them in the design structure. These values can be amended at any time through the design process.

The analogy tool helps to retrieve possible analogies according to the identified analogical parameter. The analogy tool window presents the different steps that the user

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can start through either matching and retrieval, or by mapping of the discovered analogies. Options are displayed from which to choose the ones with greatest potential for further proceeding. The analogy tool uses the proposed hierarchical structure defined earlier to conduct its mapping between the different features' values identified by the designer.

A combination tool window provides the designer with the four options of combination discussed earlier, namely: systematic combination, tree random combination, vertices random combination, or total random combination. It also asks for input of his/her design options where the designer feeds the system with the options to which he wants to apply the combination. The options can be chosen from variable knowledge domains, including the proposed alternatives or the ones previously stored.

An evolution tool window gives the designer the two options for evolution: cross over and mutation. As with the combination tool he/she feeds the system with the options on which to perform evolution methods. These options are taken from the same knowledge domains mentioned previously. The designer can decide on the initial alternatives to feed the system and then apply the combination and evolution tools on the same concepts chosen. A case study application explaining the various developed tools is discussed in the following section.

5. Application of the proposed system

To validate the system, a case study is used to demonstrate the capabilities of the CDT system through the design process focusing on the creative tools adopted within the concept generation stage. The domain of kitchen appliances is chosen using a coffee making machine as an example.

The system provides the option of secure data management by providing windows to edit, add or delete any unrelated information from the CDT databases. The data management is categorised into two major parts: general and specific. The general part deals with defining design domains, products, components, items, and features. Features incorporate defining behaviours, functions, structure categories and structure category items. The combination of all these data forms the background from which the designer identifies the specific data for his/her design project.

The design process usually starts with the preparation stage. Problem formulation begins following a client meeting where the objectives, requirements, and constraints are identified. The requirements include defining the design problem domain, products to be designed, the various components and items of the required product, as proposed by the designer, based on his search through the data provided. The developed CDT system has the capability of updating the databases regarding the problem domain, products, and design representation according to the designer's input. Certain constraints are applied in consideration of the different components and how their functions relate to one another. Searching for necessary information and different existing samples constitute an important part of the preparation stage. The search is conducted on items, components, samples, and technical information using either specified features, or a general search using the World Wide Web.

In the case demonstrated the CDT system is provided with some existing samples of coffee makers upon which to apply the tools. These examples are taken from existing products already on the market and are analysed using the design representation adopted in the CDT system. The provided sample database is constructive in the sense that it is expanded as the designer creates more samples and design options through using the CDT system. Figure (5) shows a screen shot of samples window.

Concept generation starts using the brainstorming tool. This user-friendly tool varies in some respects from the conventional concept of brainstorming. The designer can

create alternatives using the items available in the databases by combining certain items based on the identified criteria for the product. Alternatively he/she may use existing alternatives to come up with new ones via the evolution tool, or even searching for analogies in other domains or products. In reality the designer uses the various creative tools available to create his own concepts. Another possible way of brainstorming is sketching alternatives from scratch using the CAD tools provided. Figure (6) presents a sample brainstorming tool window.

Figure (5) Product samples window

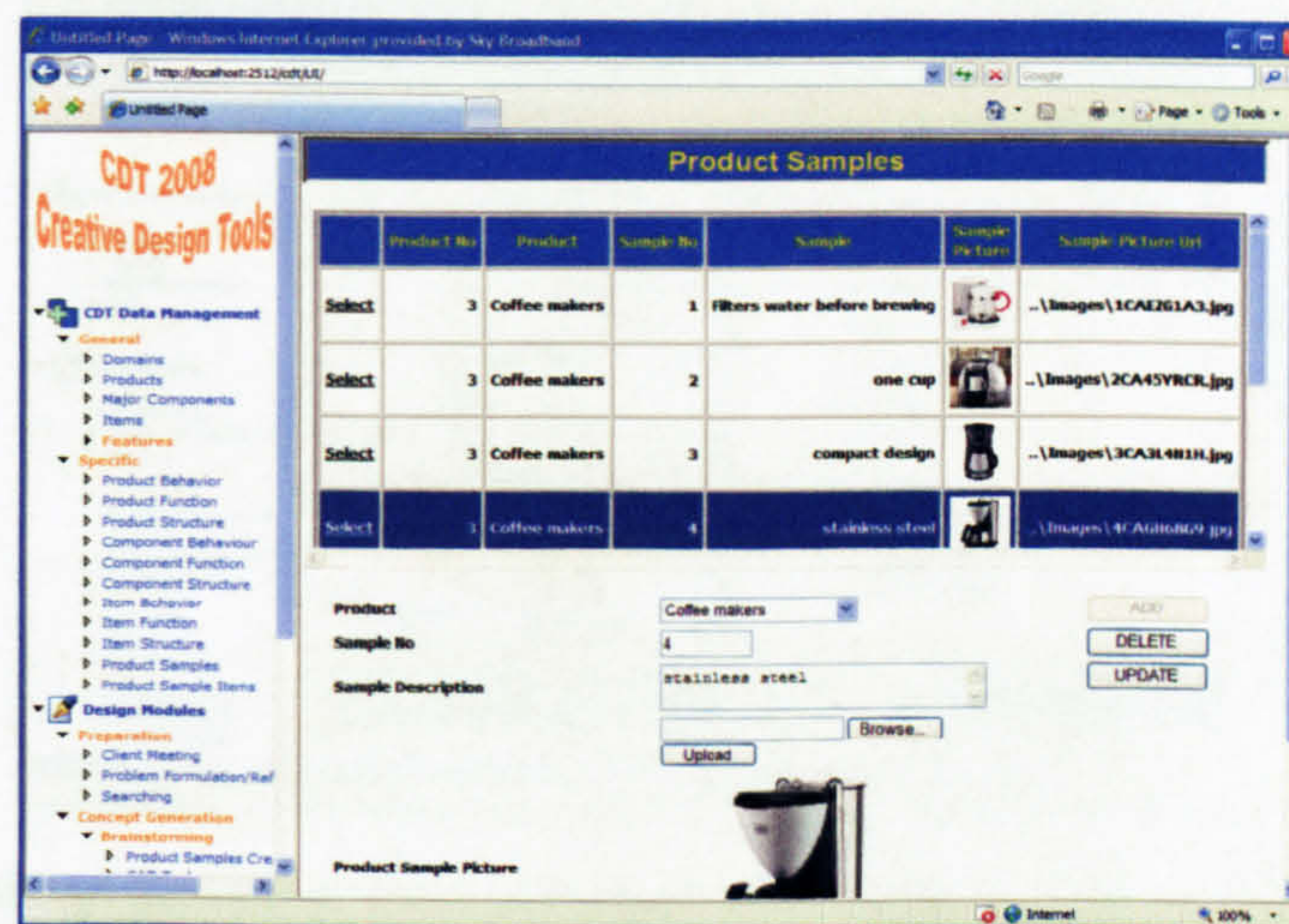
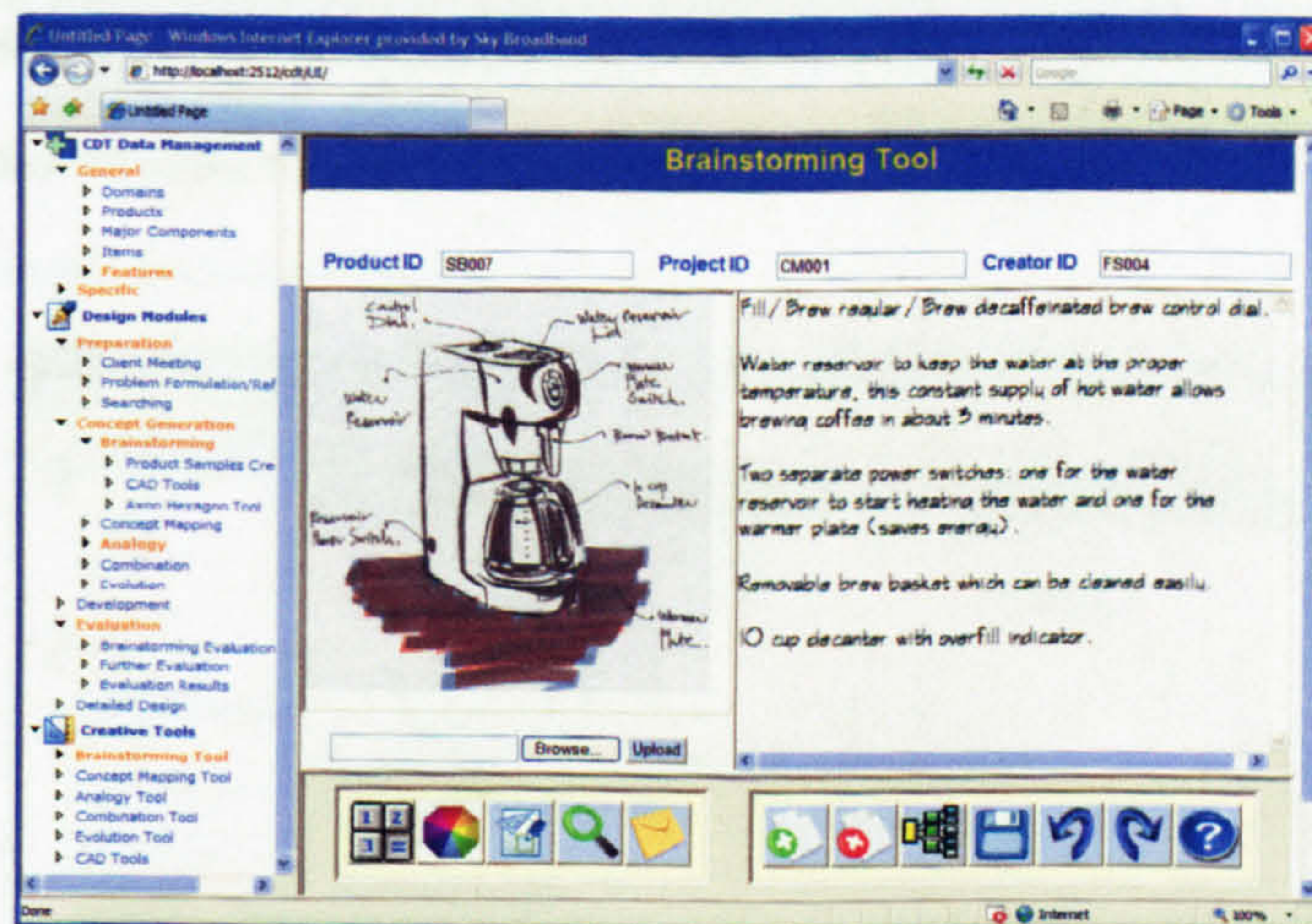


Figure (6) Brainstorming tool window

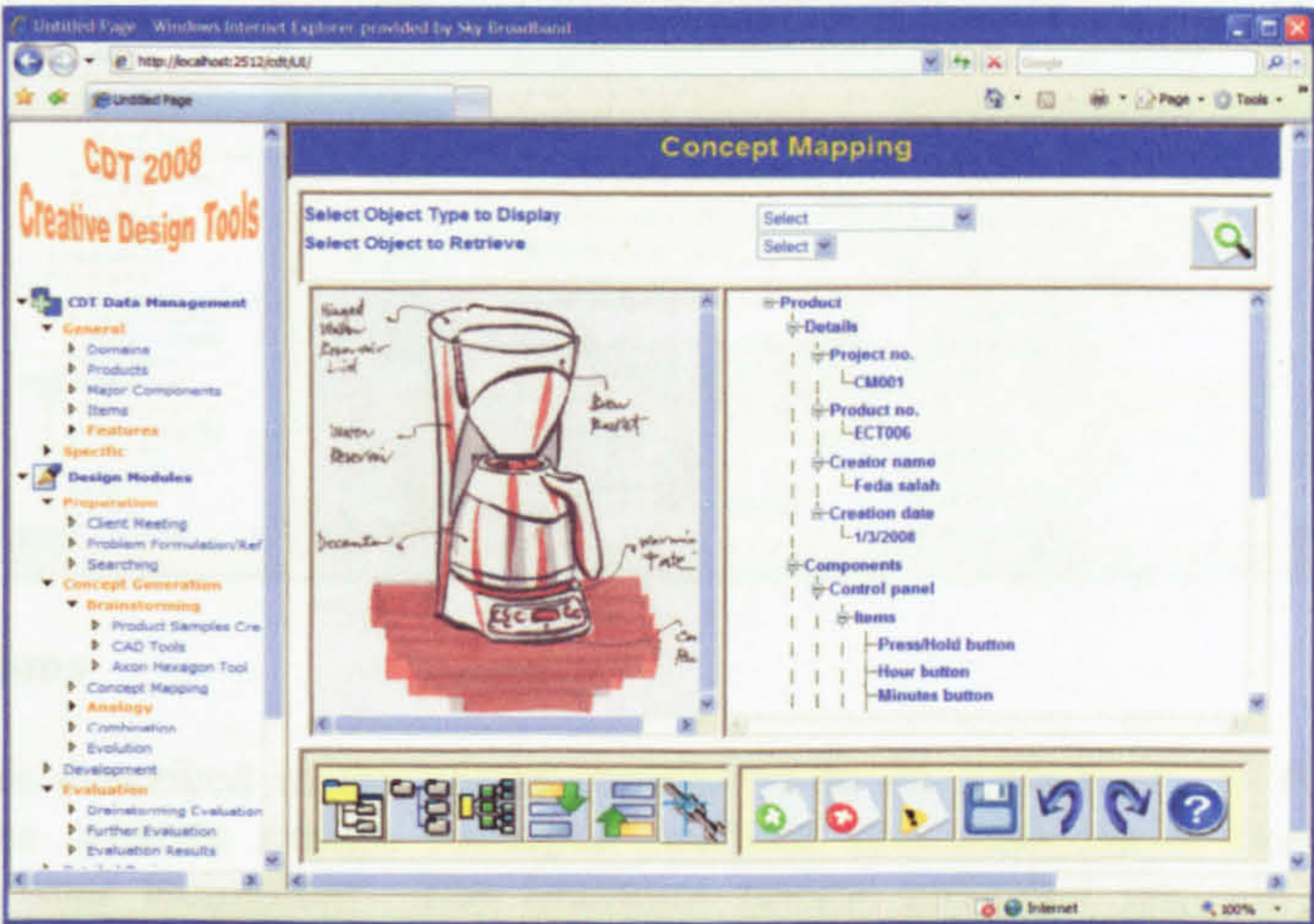


The concept map tool is used to present the product's structure in a more comprehensible way using the tree structure explained for the concept map tool. Each part of the tree structure presents an item or a component. These nodes are linked to the item model image and any related information. Figure (7) shows the concept mapping window with the coffee maker example. For more options several analogical parameters

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are chosen by the designer in the analogy window to retrieve more samples from the database with specific features in their behaviour, function and/or structural representation. More samples can be created using combination and evolution tools based on the ones chosen from analogy and brainstorming. More details will be given in future publications about these specific tools.

Figure (7) Concept mapping tool window



After concept generation, the development and evaluation of the chosen samples take place to select the most appropriate and creative ones to be taken forward for further detailing. The evaluation is conducted at three levels, the individual designer, the design team, and societal using evaluation criteria of appropriateness and novelty of idea. The societal level includes various disciplines like customers and managers; Figure (8) shows an example of brainstorming evaluation snapshot window. Evaluation results are presented altogether on request as shown in Figure (9).

Figure (8) Brainstorming evaluation window

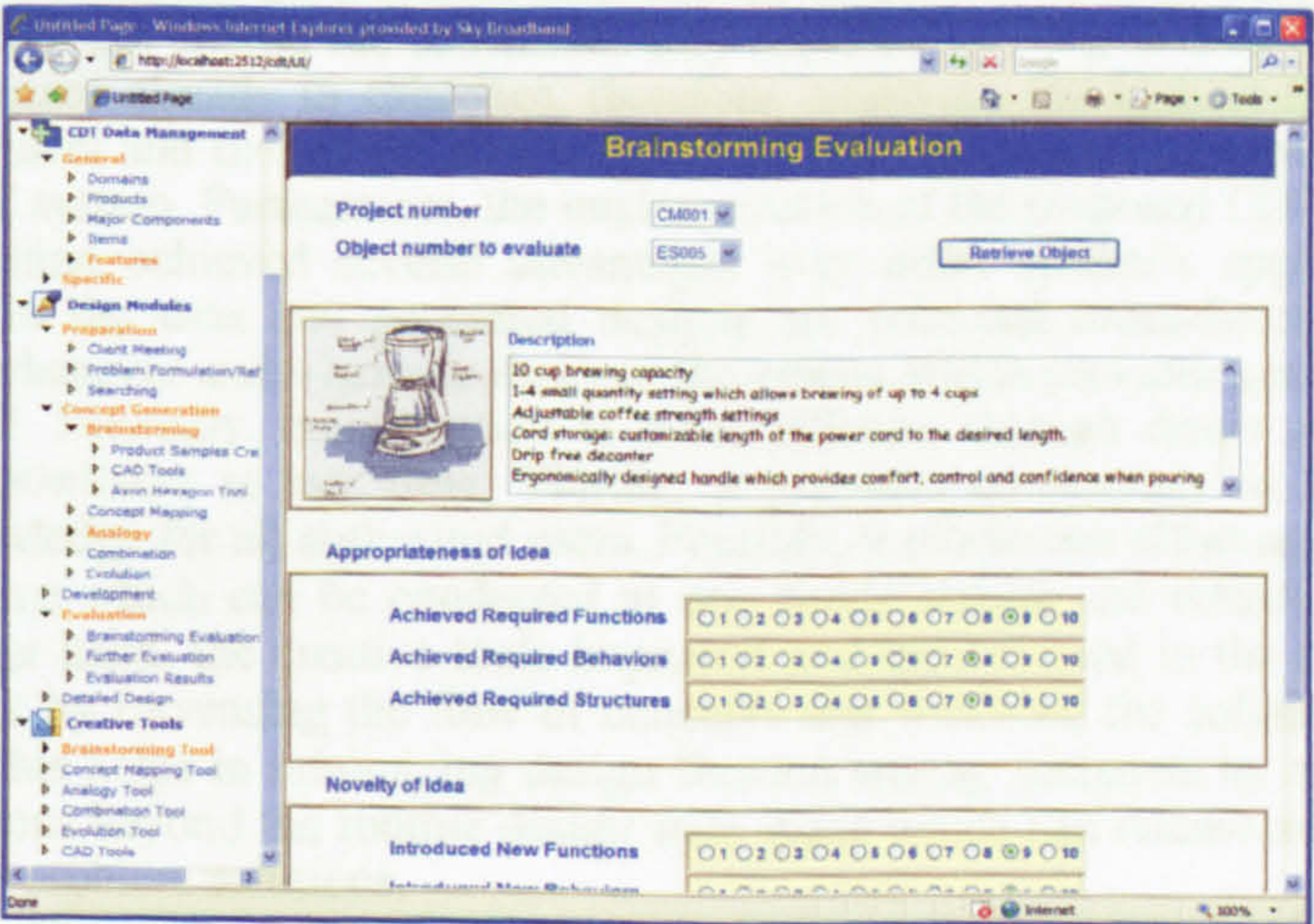
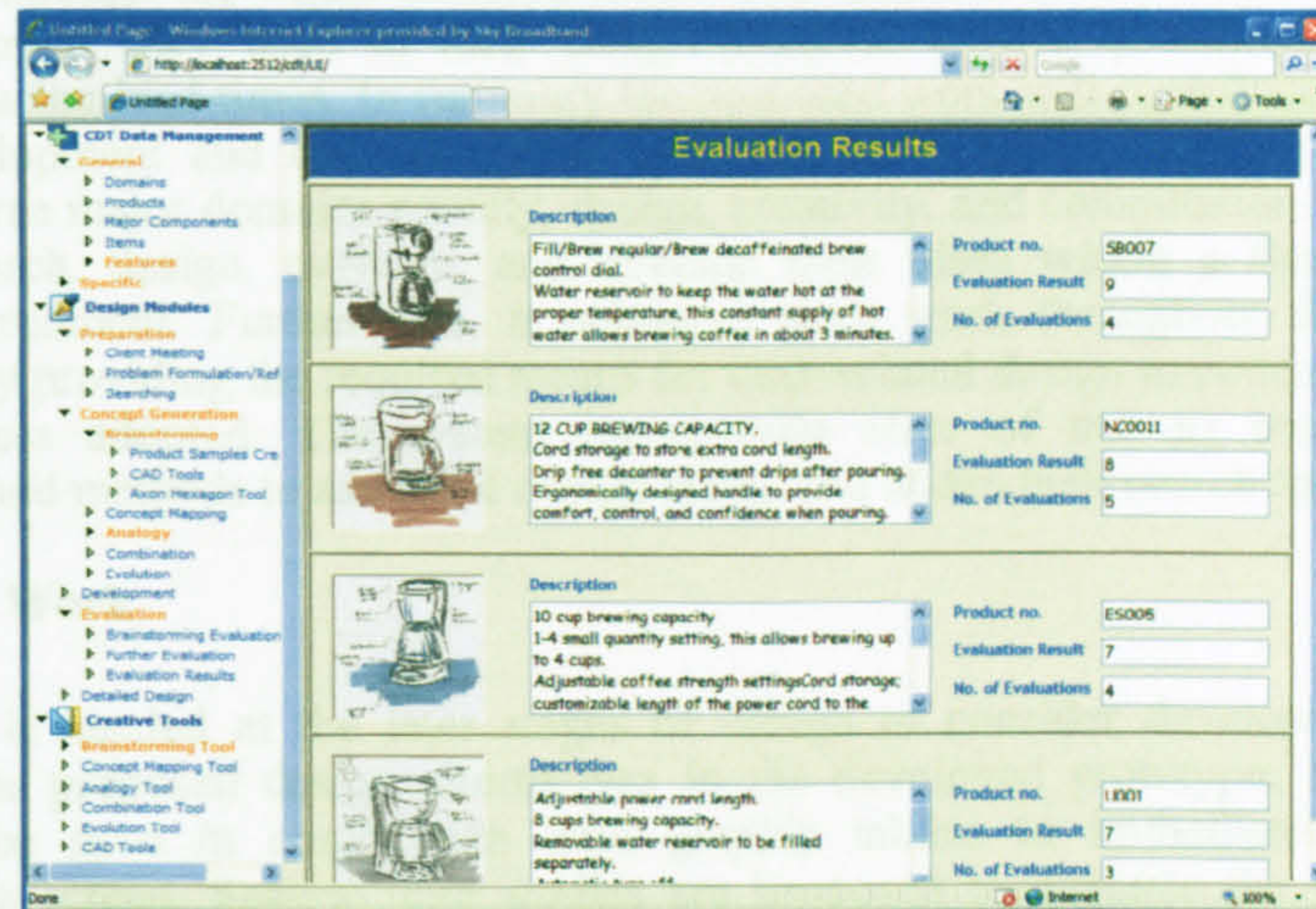


Figure (9) Evaluation results window



6. Conclusions

The research work described in this paper contributes to the philosophy of design by combining various creative design concepts, methods and tools using evolutionary computing and visual technology. The literature review indicated that all previous research studies in this area lack a holistic perspective of creative design. They have discussed individual issues in creative design but ignored the humanistic influence on such systems. Hence they have been unable to provide the basis for a holistic, realistic, practical, and well integrated computing system for the entire design process.

Many creative tools which were found to be useful in the literature for creative design thinking are computationally improved, specified, and integrated within a flexible environment which can be used by various design disciplines. A flexible hierarchical design representation is constructed and implemented in the proposed CDT system which is easy to comprehend by designers and to be used by computational creative tools to explore more design alternatives. The developed procedures for the creative tools incorporated in the proposed CDT system facilitate the constraints manageability by the designers. Designers can choose the constraints they require according to data identified or from the databases already in existence, therefore, achieving the highest flexibility between the designers and the system and integrity between the various components of the proposed CDT system. Furthermore, the implementation of the proposed CDT system as a web application achieved several advantages over other system's applications. Firstly, changes in the data and generated designs are reflected immediately to the authorised users whenever and wherever they use the system which provides similarity in the data retrieved. Secondly, collaboration is more efficient through direct access to similar design knowledge at any time. Thirdly, it provides consistency in the user interface and knowledge for all authorised users. Fourthly, it minimizes effort and cost in system maintenance which can be conducted at one single station and reflected to all users. On the other hand, the creative tools improved and incorporated in the proposed CDT system work by increasing the flow of concepts and widening the solution space through search. This helps in minimizing design fixation among designers by exploring more various options beyond the routine design state space which can release and create new directions for problem solutions.

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The proposed architecture supports designers both conceptually and computationally through the whole design process. The intention is to provide designers with all the support they need in their design problem solving processes, thereby significantly reducing lead-times. In summary the proposed work will contribute much to the design development and creative design thinking for it brings together previous research from three major domains namely, design, creativity, and computation. It allows designers to search, design, evaluate, and develop their ideas within a flexible and stimulating environment. Furthermore, it enhances team work throughout the whole design process by providing the required means for inter-related design environments and evaluation process adopted. The system incorporates state of the art computation concepts, tools, and methods to assist the design teams and widen their search space.

7. Future Work

Certainly more is needed at the later stages of design to consider development and evaluation of the proposed design alternatives in the developed prototype; free hand sketching can be used in conjunction with graphic tablets to immediately reflect sketching on the screen. Several case studies are proposed to evaluate the outcomes anticipated by the new development of the working prototype. A design team will be chosen to evaluate the case studies' results using specified criteria. Interaction between the design team and the system needs to be monitored to record any difficulties and to recommend any future enhancement of the system.

References

- ABDALLA, H., and ANDERSON, N., (2001) A Distributed E-Commerce System for Virtual Product Development Teams. *International Journal of Concurrent Engineering: Research and Application, USA*.
- ANDERSON, N. (2002) *A distributed information sharing collaborative system (DISCS)*. Unpublished thesis (PhD), De Montfort University. *Approaches to Creativity in AI and Cognitive Science*, ECAI-02, Lyon, pp. 47-54.
- BAXTER, M. (2002) *Product Design Practical Methods for the Systematic Development of New Products*. 3rd ed. Cheltenham, UK, Nelson Thornes Ltd.
- BODEN, M.A. (1994) What is creativity? In: *BODEN, M.A. Dimensions of creativity*. USA, DEKR Corporation, pp. 75-117.
- BODEN, M. (2007) *Creativity: How Does it Work?*, published by Creativity East Midlands for the Creativity: Innovation and Industry conference, 6th December 2007.
- BRUCE, M., and COOPER, R. (2000) *Creative Product Design A practical Guide to Requirements Capture Management*. 1st ed. Baffins Lane, Chichester, England, John Wiley and Sons, Ltd.
- CANDY, L. and EDMONDS E.A. (1997) Supporting the creative user: a criteria-based approach to interaction design. *Design Studies*, 18(2), pp. 185-194.
- CANDY, L., and EDMONDS, E. (1996) Creative Design of the Lotus Bicycle: Implications for Knowledge Support Systems Research. *Design Studies*, 17(1), pp. 71-90.
- CHAKRABARTI, A., and BLIGH, T. P. (2001) A Scheme for Functional Reasoning in Conceptual Design. *Design Studies*, 22(6), pp. 493-517.
- CROSS, N. (1997) Descriptive models of creative design: application to an example. *Design Studies*, 18(4), pp. 427-455.
- CROSS, N. (2000) *Engineering design methods: strategies for product design*. 3rd ed. West Sussex, John Wiley and Sons.

- CSIKSZENTMIHALYI, M. (1996) *Creativity: flow and the psychology of discovery and invention*. New York, Harper Collins.
- DARLINGTON, M. J., and CULLEY, S. J. (2004) A model of Factors Influencing the Design Requirement. *Design Studies*, 25(4), pp. 329-350.
- GARDNER, H. (1994) The Creators' Patterns. In: BODEN, M., eds. *Dimensions of Creativity*. USA, Massachusetts Institute of Technology, pp. 143-158.
- GERO, J. (1990) *Design prototypes: a knowledge representation schema for design* [WWW]. Available from: <http://www.arch.usyd.edu.au> [Accessed 08/02/2005].
- GERO, J. (2000) Computational models of innovative and creative design processes. *Technological Forecasting and Social Change*, 64, pp. 183-196.
- GERO, J. (2003) Situated computing: a new paradigm for design computing. In: CHOUTGRAJANK, A., CHAROENSLIP, E., KEATRUANGKAMALA, K., and NAKAPAN, W. (eds), *CAADRIA03*, Rangsit University, Bangkok, pp. 579-587.
- GERO, J. and KANNENGIESSER, U. (2004) The situated function-behaviour-structure framework. *Design Studies*, 25(4), pp. 373-391.
- GOMES, P., SECO, N., PEREIRA, F. C., PAIVA, P., CARREIRO, P., FERREIRA, J. L., and BENTO, C. (2006) The Importance of Retrieval in Creative Design Analogies. *Knowledge-Based Systems*, 19(7), pp. 480-488.
- GU, Z., TANG, M.X., and FRAZER, J.H. (2006) Capturing aesthetic intention during interactive evolution. *Computer-Aided Design*, 38(3), pp. 224-237.
- HOEBEN, A., and STAPPERS, P.J. (2005) Direct talkback in computer supported tools for the conceptual stage of design. *Knowledge-Based Systems*, 18(8), pp. 407-413.
- HUANG, Y. (2008) Investigating the cognitive behaviour of generating idea sketches through neural network systems. *Design Studies*, 29(1), pp. 70-92.
- JANSSON, D.G. and SMITH, S.M. (1991) Design fixation. *Design Studies*, 12(1) pp. 3-11.
- JONSON, B. (2005) Design ideation: the conceptual sketch in the digital age. *Design Studies*, 26(6), pp. 613-624.
- JOHNSON, H., and CARRUTHERS, L. (2006) Supporting Creative and Reflective Processes. *International Journal of Human-Computer Studies*, 64(10), pp. 998-1030.
- KARA, L.B., SHIMADA, K., and MARMALEFSKY, S.D. (2007) An evaluation of user experience with a sketch-based 3D modelling system. *Computers and Graphics*, 31(4), pp. 580-597.
- KIM, M. H., KIM, Y. S., LEE, H.S., and PARK, J. A. (2007) An Underlying Cognitive Aspect of Design Creativity: Limited Commitment Mode Control Strategy. *Design Studies*, 28(6), pp. 585-604.
- KOKOTOVITCH, V. (2007) Problem Analysis and Thinking Tools: An Empirical Study of Non-Hierarchical Mind Mapping. *Design Studies*, 29(1), pp. 49-69.
- LAWSON, B. (1997) *How designers think: the design process demystified*. Third edition. Oxford, Butterworth-Heinemann.
- LAWSON, B. (2004) Schemata, Gambits and Precedent: Some Factors in Design Expertise. *Design Studies*, 25(5), pp. 443-457.
- LI, W.D. et al (2005) Collaborative computer-aided design: research and development status. *Computer-Aided Design*, 37(9), pp. 931-940.
- LIN, M.C., WANG, C.C., CHEN, M.S., and CHANG, C.A. (2008) Using AIIP and TOPSIS approaches in customer-driven product design process. *Computers in Industry*, 59(1), pp. 17-31.
- LIU, H., TANG, M. and FRAZER, H. (2004) Supporting creative design in a visual evolutionary computing environment. *Advances in Engineering Software*, 35(5), pp. 261-271.
- LIU, Y.-C., BLIGH, T., and CHAKRABARTI, A. (2003) Towards an Ideal Approach for Concept Generation. *Design Studies*, 24(4), pp. 341-355.
- LIU, Y.T. (2000) Creativity or novelty? *Design Studies*, 21(3), pp. 261-276.

Creative Design Tools (CDT): Stimulating creative design thinking

- MOK, C.K., CHIN, K.S., and LAN, H. (2008) An internet-based intelligent design system for injection moulds. *Robotics and Computer-Integrated Manufacturing*, 24(1), pp. 1-15.
- OXMAN, R. (2004) Think maps: teaching design thinking in design education. *Design Studies*, 25(1), pp. 63-91.
- PEREIRA, F.C., and CARDOSO, A. (2006) Experiments with free concept generation in Divago. *Knowledge-Based Systems*, 19(7), pp. 459-470.
- PURCELL, A.T. and GERO, J.S. (1996) Design and other types of fixation. *Design Studies*, 17(4), pp. 363-383.
- RODGERS, P. A., GREEN, G., and MCGOWN, A. (2000) Using Concept Sketches to Track Design Progress. *Design Studies*, 21 (5), pp. 451-464.
- SEGRS, N. M., DE VRIES, B., and ACHTEN, H. H. (2005) Do Word Graphs Stimulate Design? *Design Studies*, 26(6), pp. 625-647.
- SIMON, H.A. (1988) Creativity and motivation. *New Ideas in Psychology*, 6(2), pp. 177-181.
- TANG, H.H. and GERO, J. (2002) A cognitive method to measure potential creativity in designing. In: BENTO, C., CARDOSO, A. and WIGGINS, G. (eds) *Workshop 17 – Creative Systems: Approaches to Creativity in AI and Cognitive Science, ECAI-02*, Lyon, pp. 47-54.
- TSENG, C.J. and ABDALLA, H. (2004) A human-computer system for collaborative design (HCSCD). *Journal of Materials Processing Technology*, 155-156 (2), pp. 1964-1971.
- TSENG, K.C. (2005) *A human-centered system for collaborative product development*. Unpublished thesis (PhD), De Montfort University.
- VAN DER LUGT, R. (2000) Developing a graphic tool for creative problem solving in design groups. *Design Studies*, 21(5), pp. 505-522.
- VAN DER LUGT, R. (2005) How sketching can affect the idea generation process in design group meetings. *Design Studies*, 26(2), pp. 101-122.
- VERSTIJNEN, I.M. et al. (1998) Sketching and creative discovery. *Design Studies*, 19(4), pp. 519-546.
- VISSER, W. (1996) Two Functions of Analogical Reasoning in Design: a Cognitive-Psychology Approach. *Design Studies*, 17(4), pp. 417-434.
- WARD, T.B. (2007) Creative Cognition as a Window on Creativity. *Methods*, 42(1), pp. 28-37.
- WON, P.H. (2001) The comparison between visual thinking using computer and conventional media in the concept generation stages of design. *Automation in Construction*, 10(3), pp. 319-325.
- YE, X., LIU, H., CHEN, Z., PAN, X., and ZHANG, S. (2007) Reverse innovative design – an integrated product design methodology. *Computer-Aided Design*, doi:10.1016/j.cad.2007.07.006
- YIN, Y., VANIDES, J., RUIZ-PREMO, M.A., AYALA, C.C. and SHAVELSON, R.J. (2005) Comparison of two concept mapping techniques: Implications for scoring, interpretation, and use. *Journal of Research in Science Teaching*, 42(2), pp. 166-184.
- ZIZ-AY, A. and REICH, Y. (2005) SOS subjective objective system for generating optimal product concepts. *Design Studies*, 26(5), pp. 509-533.

A Knowledge-Based System for Enhancing Conceptual Design

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Abstract

This research paper presents a knowledge-based system to enhance creative conceptual design. Market globalization and technology advances require fast adaptation to customer needs by being creative and competent. Literature review and current practices in design constituted the basis for the developed Creative Design Tools (CDT) system architecture. The developed system provides users with an integrated and flexible creative design environment to enhance their creative conceptual thinking. Such design environment requires the integration of many components namely: design process, creative tools, and design knowledge within a highly collaborative interactive human-computer interface. The CDT system was implemented as a web application which was integrated with various creative methods. It encompasses knowledge databases, creative tools, and five design modules namely: preparation, concept generation, design development, evaluation, and detailed design. The developed CDT system was validated using a case study to show its capabilities in exploring conceptual ideas.

Keywords

Creative design; creative tools; design thinking; knowledge based systems; creative systems; collaborative systems; design creativity, design process.

1. Introduction

Competence in the future global market requires fast response to customer needs with immense capabilities in designing and producing creative competitive products. Since this research adopted the view of creativity as a learnt skill, the development of tools and techniques to enhance creative design thinking among design groups is essential. Furthermore, the advancement of computer technologies is developing enormously. Very rapid changes occurred particularly in becoming more user-friendly, enlarging storing capabilities, speeding in processing information, and introducing of World Wide Web that connected the whole world together and cancelled any distances.

Therefore, these rapid changes in technology require rapid adaptation from our side. Designers are one sector of the society that needs to adapt as fast as the speed of technological advances. These technological developments can enhance designers' work tremendously if properly utilized. Design computation is to support design groups and enhance their creative thinking for new product development, collaboration, and short lead time for manufacturing Abdalla (1999) Tseng and Abdalla (2004).

The main aim is to provide design groups with flexible design environments to escape the routine design space to a more non-routine design solution space Hori (1997). The identification of new design knowledge by fluent interaction between designers and knowledge Candy and Edmonds (1996), flexibility in defining requirements and constraints, integrity of the whole design process with creative methods and tools that can assist the creation of new design solution spaces with several channels of exploration open in parallel Shneiderman (2000) Hewett (2005), are considered essential solutions to achieve that main aim.

Creativity involves four components: the creative process, creative product, creative person, and creative situation Eysenck (1994). Abstraction is vital to the creative process through using old information and expressing it in an abstract form Ward et al (1995). This helps the identification of goals and the development of new creative ideas. To meet these goals other means such as processes and methods are essential. Three types of creativity are distinguished according to the process used in generating creative ideas: combinational, exploratory, and transformational Boden (2007). Various ways are relevant to encourage creativity depending on its type. For combinational type as an example; widening the general design knowledge, experimenting unfamiliar combinations, and an evaluating criteria to pick the proper solutions are proposed.

Creative methods usually work by increasing the flow of ideas, removing mental blocks, and widening the search area for solutions, Cross (2000). These creative methods can be achieved by using special type of tools. For example to increase the flow of ideas brainstorming can be used to produce a large number of alternatives. Furthermore, the use of analogical thinking can eliminate mental blocks. On the other hand widening the search space can be achieved through evolutionary and combinational tools Bentley (1997) Bentley and Corne (2002) Gero (1999).

Various creative design models were proposed in the literature. Simon (1988) model was based on the personal view of creativity by hypothesizing that creativity is a special kind of problem solving behavior which satisfies novelty and value of the resulted product for the designer and his/her culture, unconventional thinking, high motivation, and ill defined problems to be formulated through the design process. On the other hand, Csikszentmihalyi (1988) (1996) developed the social-cultural creativity model on where is creativity not on what

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is creativity. His framework composed of three major elements: the person, the field, and the domain. The occurrence of a creative idea, object, or action is determined by the jointly relation between those three elements. An idea is realized as creative if the person recognizes it and the society additionally. Based on those two models Liu (2000) proposed the dual generate-and-test model. This dual model encapsulates two generate-and-test loops; one at the level of the individual, and the other at the level of society.

Creative design is not fixing the problem and searching for solution, it is more into developing and refining both the problem formulation and the solution Dorst (2001). This can be achieved by repetition of analysis, synthesis, and evaluation processes between the problem space and the solution space. The essential stages of divergence, transformation, and convergence were proposed in Hsiao and Chou (2004) model of creativity-based design process. Their method contained personal behaviors of human sensuousness such as looking, thinking, comparing, and describing accompanied by stimulation which is an extrinsic influence of the environment.

Requirements capture (RC) is usually at the front end of the design process in any new product development. It is the process of research and identification of the customer, user, market, design, and technical requirements. It is essential to conduct a thorough (RC) through information gathering, information transformation, and requirements generation to provide a basis to build design solutions and synthesis Bruce and Cooper (2000) Darlington and Culley (2004).

Conceptual design is one of the early stages of design that demands the greatest creativity. Its main aim is to produce design principles concerning the product form and function to satisfy requirements and be competent Baxter (2002). Lots of concepts are usually generated at this stage. Two main steps of divergence and convergence are identified in conceptual design and were discussed by various researchers Pugh (1991) and Cross (1994). A multiple divergence convergence approach was proposed to increase the number of the generated concepts to reach a level beyond abstraction to be understood by designers and reduce the solution space Liu et al (2003). It was recognized that visualization facilitate the concept generation in any design process Dahl et al (2001) Won (2001). The designers externalize their ideas using sketching or other ways of representations such as diagrams, concept maps, or documents using computers. The represented results inspire designers to generate new ideas or concepts Nakakoji et al (2000) Hoeben and Stappers (2005).

Creative problem solving in design using visual creative tools were discussed in the literature. Visual and classical brainstorming proved to assist design groups in their concept generation process Van Der Lugt (2000). Concept mapping proved to support creative thinking in general Buzan (2002) and creative design thinking in specific Anderson and Abdalla (2002) Anderson (2002) and Yin et al (2005). It presents a holistic approach by making the structure of the problem more readable and act as memory

aids to review the design problem at any stage of the design process Kokotovitch (2007).

Analogical reasoning is another technique to widen the design solution space. It is the transfer of knowledge between various domains based on similarities between the target and the source space. It involves three major phases: (1) identifying the source candidates for analogy matching and retrieval (2) mapping the source candidate with the target (3) transferring knowledge between the source and the target Gero and Kazakov (1999) and Gomes et al (2006).

It was recognized that combination and evolution play an important role in production of creative work in various disciplines and design is one of them. Combination involves the combining of two design concepts or subsets of them from similar or dissimilar unrelated ideas Gero (1999). The combination can occur at various levels. Furthermore, evolutionary search algorithms look at a population of slightly different solutions at once, and then through cross over and mutation new generations are created. This tool proved to produce creative design solutions Bentley and Wakefield (1996) and Gero and Kazakov (1999).

The literature review indicated that a holistic approach is needed to enhance creative design thinking among design teams by providing an integrated flexible design environment with the proper knowledge, processes, and creative tools. Several limitations were addressed in the existing creative design models. They lacked the integration of various creative tools and processes with the proper constructive design knowledge, the use of flexible design representation which can be adjusted by designers and reflected to all users immediately, and the distance collaboration among design teams in the early stages of design at various locations.

To overcome those limitations, the CDT system has been developed taking into consideration all the aspects of creative design approaches the creative process, creative product, creative person, and creative situation.

2. Current practices in design

An empirical survey was conducted to determine designers' current practices such as adopted design processes, used tools, followed evaluation criteria, and preferred design environments. One-to-one interview was chosen to conduct the survey. A sample of 30 designers from various design disciplines was chosen namely: spatial design, product design, graphic design, and multimedia. By using open ended interview structure more relevant practices were revealed. Although it is much more difficult to analyze such type of interviews, it provides more suitable objective results. The collected data was analyzed using SPSS application software. Two descriptive statistics were applied; the frequencies' tables and bar charts. The results of designer's current practices are displayed in the following sections.

2.1 Tools that stimulate creative design thinking

The objective of this section is to investigate the tools used by designers and how they relate to the ones addressed in the literature. Various creative thinking tools were encountered; the results are presented in Table 1 showing the frequency of occurrence.

		Responses		Percent of Cases
		N	Percent	
Creative Design Techniques	Search and Widening Knowledge	25	18.8%	83.3%
	Brainstorming Technique	13	9.8%	43.3%
	Analogy Technique	5	3.8%	16.7%
	Combination Technique	1	.8%	3.3%
	Evolution Technique	1	.8%	3.3%
	Emergence	3	2.3%	10.0%
	Concept Mapping	9	6.8%	30.0%
	Collaboration	16	12.0%	53.3%
	Technological Advancements and Visual Tools	24	18.0%	80.0%
	Market and Client Needs Analysis	13	9.8%	43.3%
	Impose Constraints	5	3.8%	16.7%
	Six Hats Roles	3	2.3%	10.0%
	Sample Materials	4	3.0%	13.3%
	Cultural Dimensions	2	1.5%	6.7%
	Experience	4	3.0%	13.3%
	Model making	5	3.8%	16.7%
Total		133	100.0%	443.3%

Table 1 Creative design tools

The higher responses were recognized for search and widening knowledge, technological advancement and visual tools, collaboration, market and client needs analysis, and brainstorming respectively. On the other hand the lowest responses were perceived for combination and evolution tools, although they were addressed in the literature for their high competence in creative design solutions. The proposed framework integrated the highly recognized tools with the least recognized ones to provide a friendly, effective, creative, and concurrent design environment.

2.2 Design processes

The analysis of the design process given by designers was categorized into six major process stages. The process stages given by each designer were classified in order into those categories. The following bar charts give an indication of how designers approach design problem solving. Fig.1 shows the first process bar chart with the highest percentage

for defining requirements and objectives process. Fig.2 and Fig.3 show the second and third process bar charts respectively with the highest percentage for conceptual design. Furthermore, the fourth process bar chart in Fig. 4 shows the highest percentage for design development followed by design evaluation. Finally, the fifth and sixth processes in Fig.5 and Fig.6 respectively show the highest percentage for detailed design.

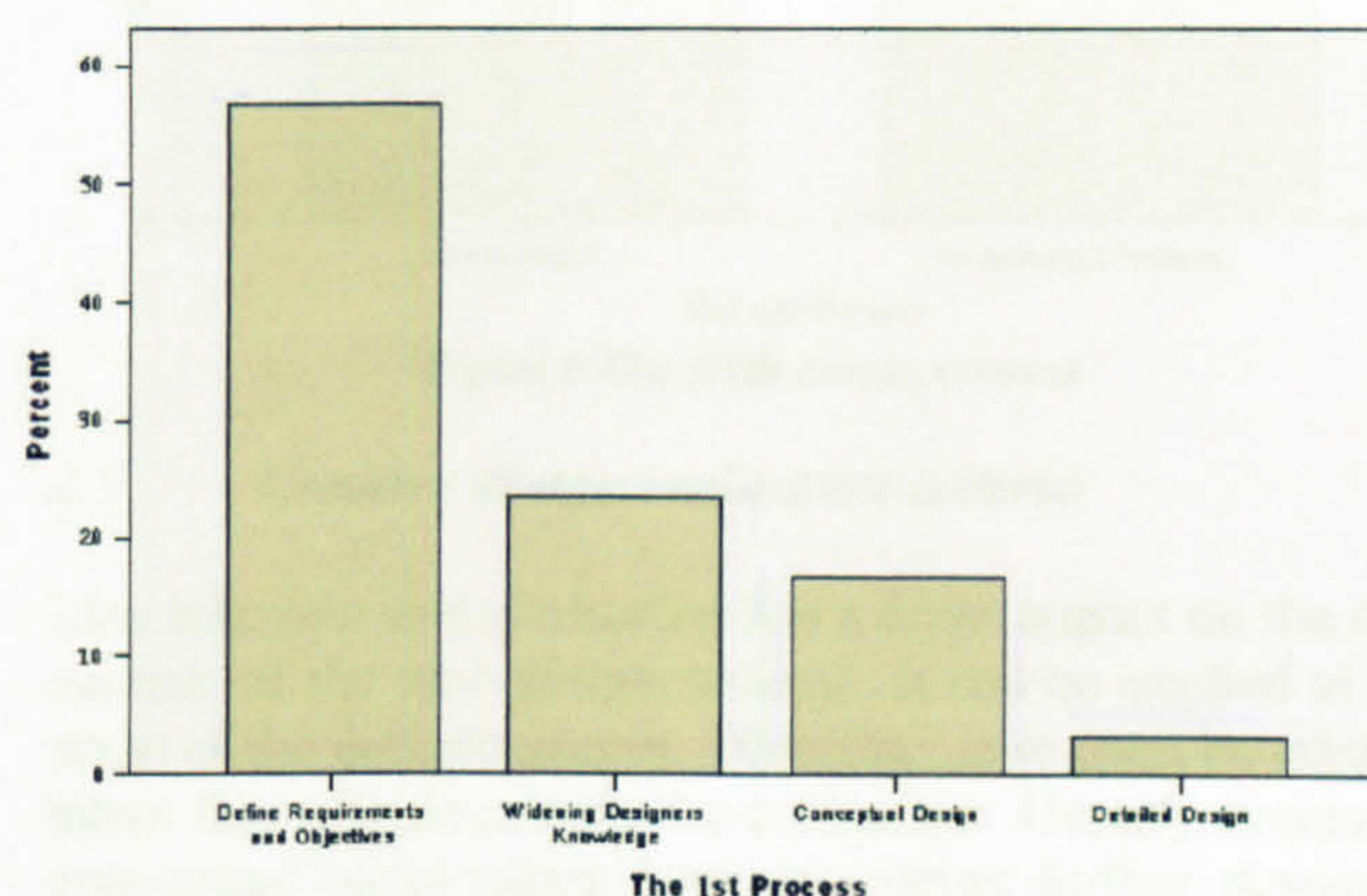


Figure 1 The first design process

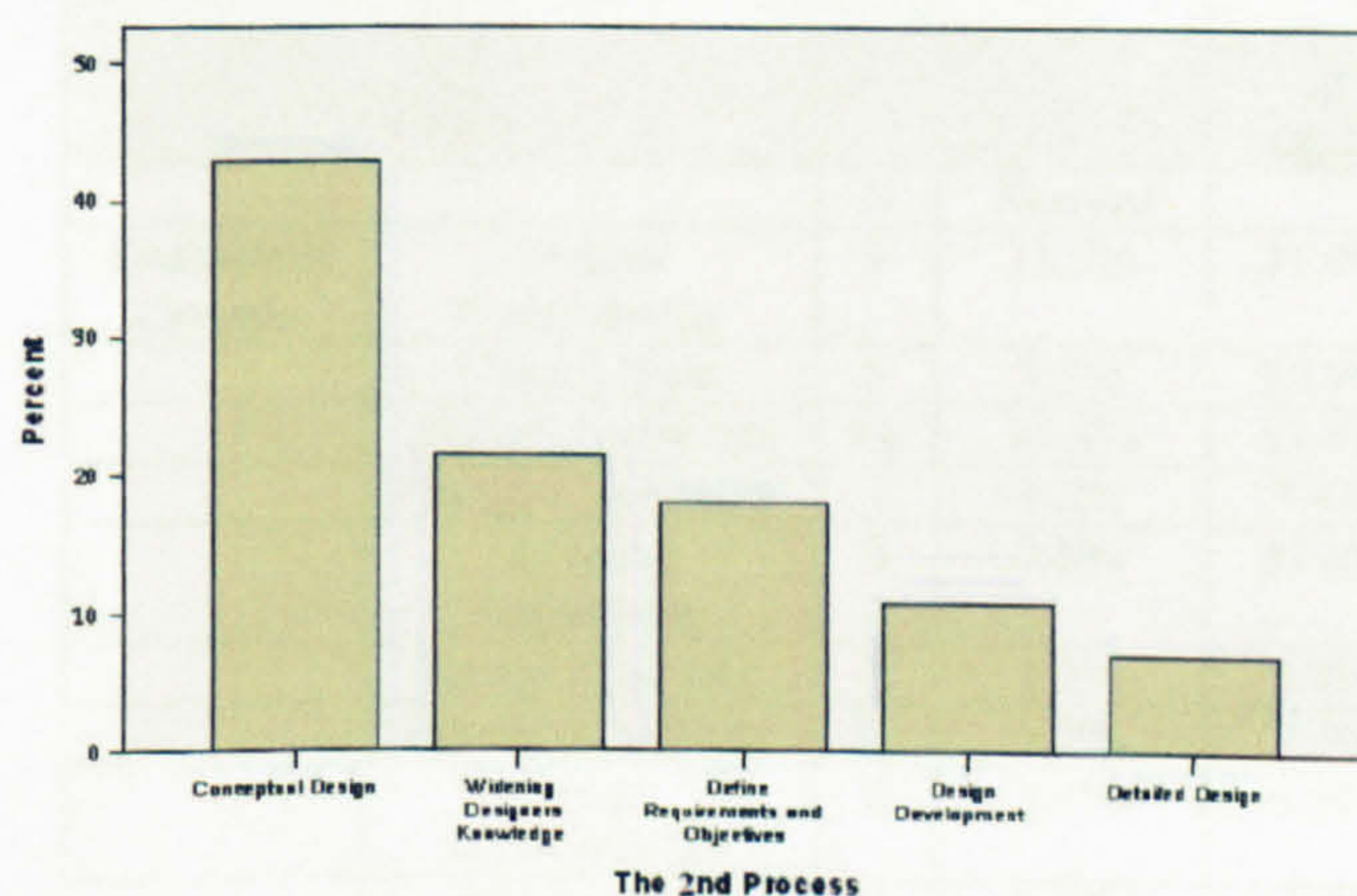


Figure 2 The second design process

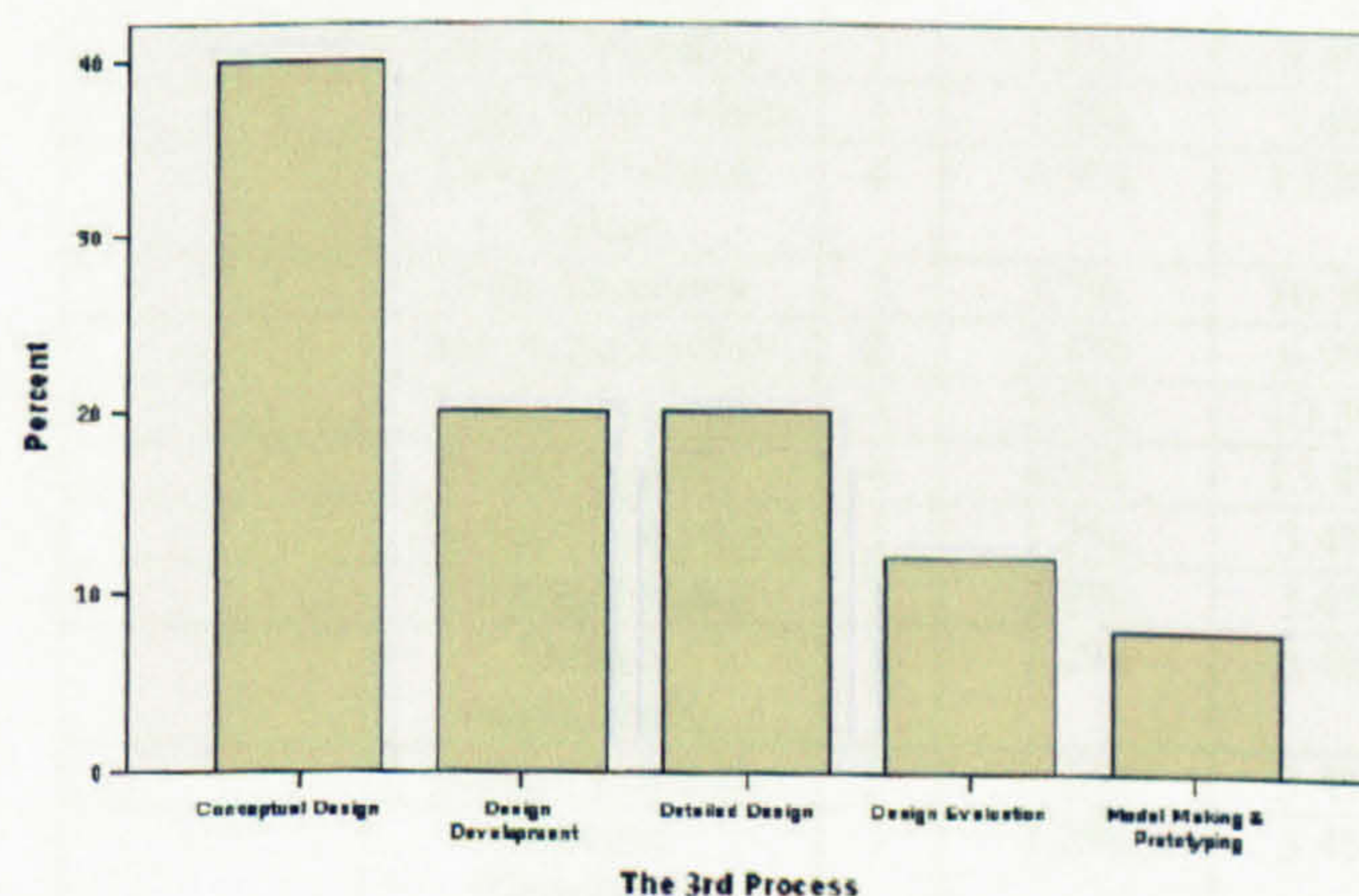


Figure 3 The third design process

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The major important issue concluded was the nonlinearity of the design process; each designer approached the design process differently. Although from the majority of cases it was recognized there was a preference for a general design process which was previously addressed in the literature.

The proposed design process modules were constructed based on the literature and supported by the interview results. For the ease of classification the two processes of defining requirements and objectives, and widening designer's knowledge were combined in one process named preparation. Furthermore, the prototyping and model making process was integrated with the evaluation process. The design process proposed includes five general stages: preparation, concept generation, development, evaluation, and detailed design. The nonlinearity of the design process was taken into consideration in the proposed system by being flexible in starting the design process from the stage that suits the designer preference.

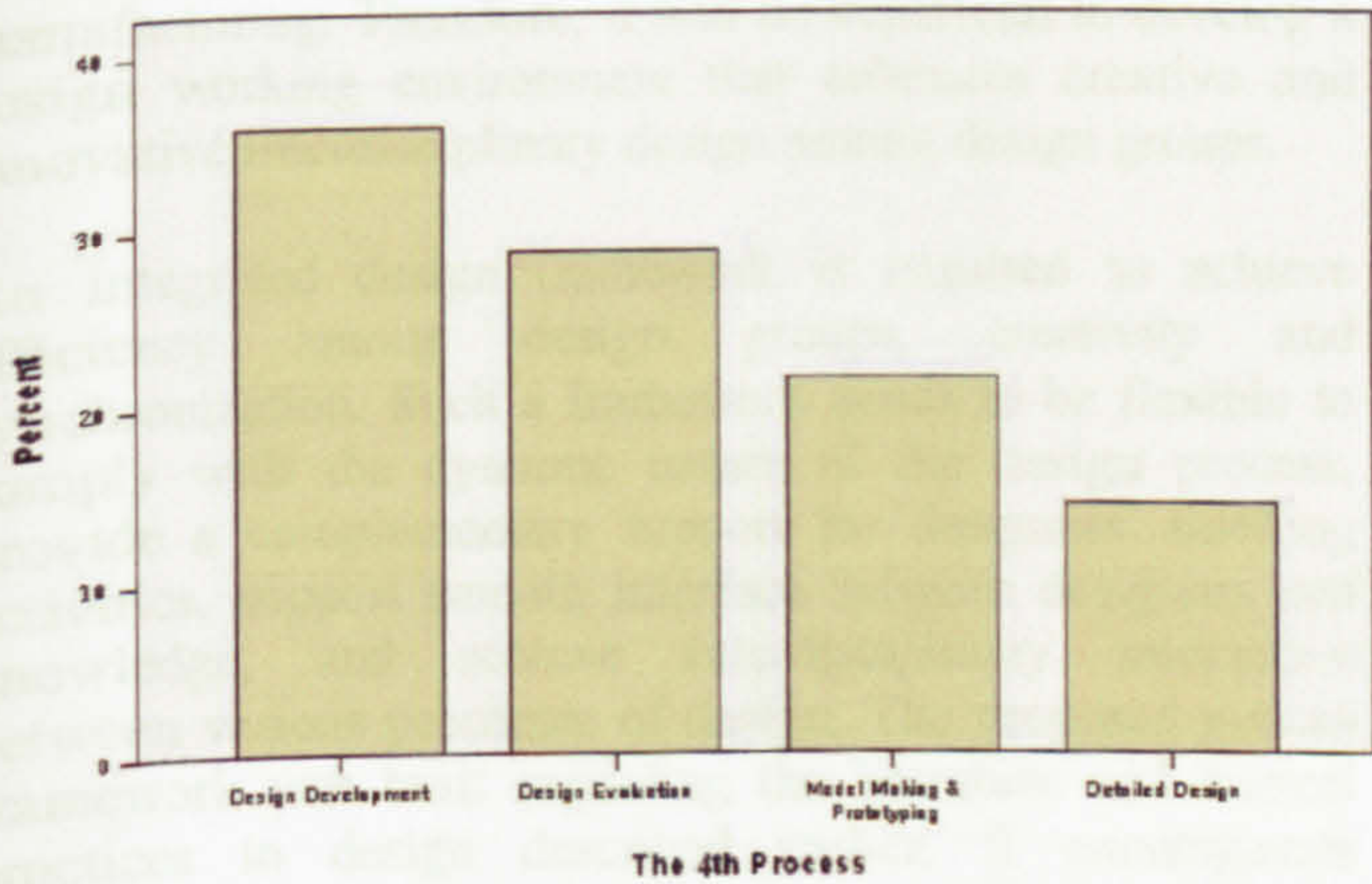


Figure 4 The fourth design process

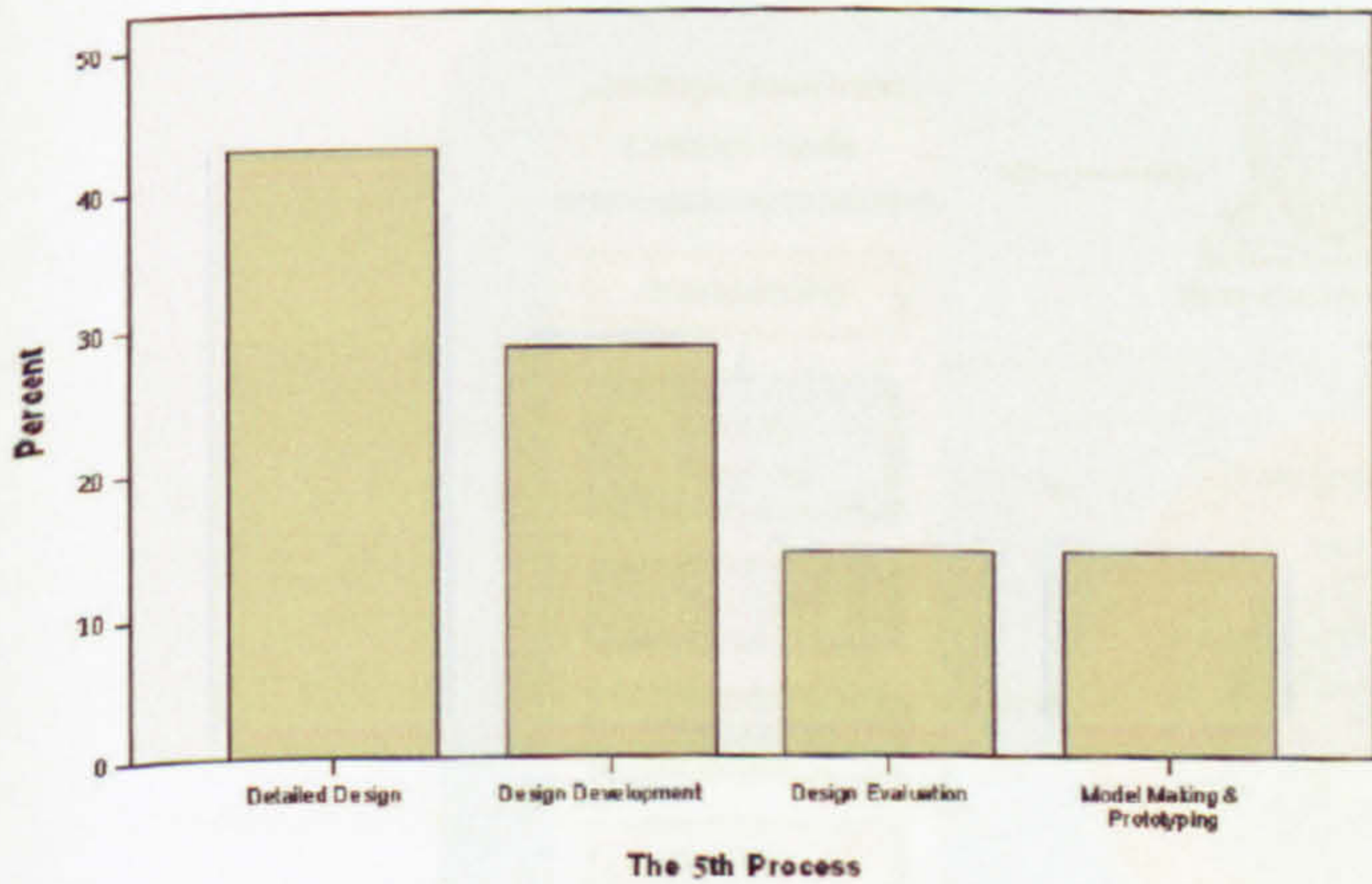


Figure 5 The fifth design process

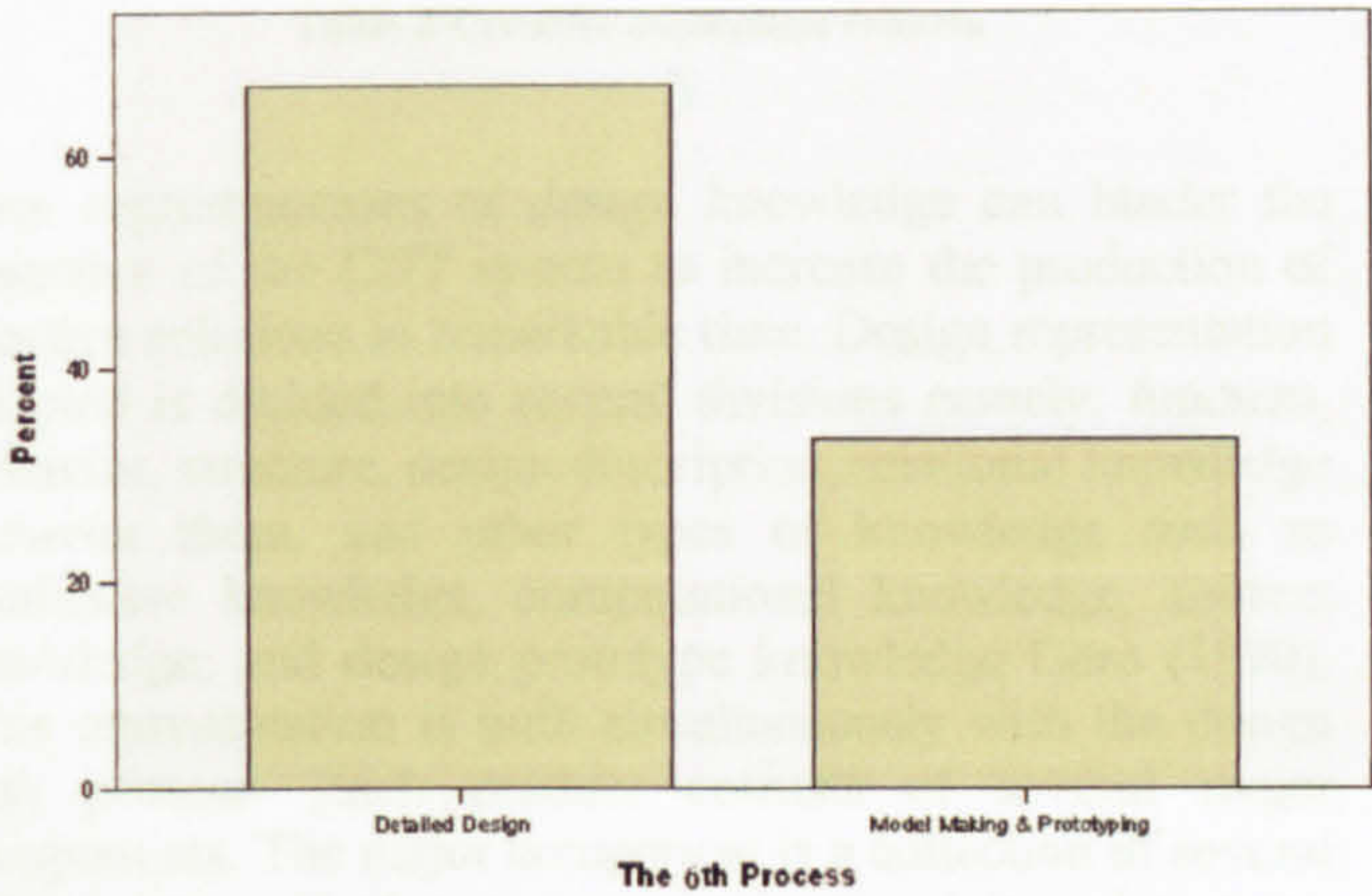


Figure 6 The sixth design process

2.3 Creative design evaluation criteria

Idea selection and evaluation has a large impact on the final success of the new design concept. It can be applied at any stage of the design process. Therefore, care must be taken to adopt the suitable criteria for evaluation. Usually evaluating conceptual ideas varies from evaluating further developed designs. The criteria used in conceptual ideas are more generic than the one used in more detailed ideas.

		Responses		Percent of Cases
		N	Percent	
Evaluation Criteria	Design Functionality	9	11.0%	31.0%
	Unique Ideas	6	7.3%	20.7%
	Design Aesthetics	12	14.6%	41.4%
	Design Practicality	1	1.2%	3.4%
	Achieve Objectives	8	9.8%	27.6%
	Design Usability	1	1.2%	3.4%
	Design Simplicity	1	1.2%	3.4%
	Design Compatibility	2	2.4%	6.9%
	Design Cost	7	8.5%	24.1%
	Design Likeability	6	7.3%	20.7%
	Design Usefulness	1	1.2%	3.4%
	Design Novelty	4	4.9%	13.8%
	Design Viability	1	1.2%	3.4%
	Design Mechanism	1	1.2%	3.4%
	Design Cultural Values	4	4.9%	13.8%
	Users Feedback	3	3.7%	10.3%
	Design Suitability	2	2.4%	6.9%
	Materials Used	3	3.7%	10.3%
	Design Quality	4	4.9%	13.8%
	Design Efficiency	1	1.2%	3.4%
	Testing Results	1	1.2%	3.4%
	Design Applicability	1	1.2%	3.4%
	Design Context	1	1.2%	3.4%
	Design Complexity	1	1.2%	3.4%
	Manufacturability	1	1.2%	3.4%
Total		82	100.0%	282.8%

The conducted interviews addressed multi-criteria for creative design evaluation. A result of 25 criteria with their frequencies is shown in table 2. These criteria were divided into few broader classifications which incorporate appropriateness and uniqueness. Any design is considered creative if it was appropriate and unique, if it was unique but not appropriate it will not be considered creative in that particular situation.

This survey discussed various design current practices and revealed some of the adopted creative tools, processes, and evaluation criteria which provided a constructive foundation for developing the CDT system.

3. The proposed CDT Creative Design Tools system

At the early stages of the design process, designers from various disciplines need to collaborate to produce creative solutions that reduce the need for elaboration in later stages of the design process and shorten the lead time for manufacturing. Therefore, it will be beneficial to develop a design working environment that enhances creative and innovative interdisciplinary design among design groups.

An integrated design framework is required to achieve efficiency among design groups, creativity and synchronization. Such a framework needs to be flexible to comply with the dynamic nature of the design process, provide a complementary support for designers' thinking activities, support smooth interface between designers and knowledge, and achieve interdisciplinary interaction between various processes of design. The proposed system framework was built regarding the literature and current practices in design described earlier. It encompasses constructive knowledge databases, creative tools, five design modules, and a user friendly interface. The overall structure of the CDT system is shown in Fig.7.

3.1 Design representation and databases

Table 2 Creative evaluation criteria

Poor representations of design knowledge can hinder the objective of the CDT system to increase the production of creative solutions in remarkable time. Design representation adopted is divided into several divisions namely: function, behavior, structure, design description, relational knowledge between them, and other types of knowledge such as qualitative knowledge, computational knowledge, context knowledge, and design prototype knowledge Gero (1990). This representation is built simultaneously with the design task process. Each product consists of several major components. The major component is a collection of several related items. Each major component and item has some features classified as functional, behavioral, and structural. The major component or item can possess many functions and these functions can be identified in many items or components. The same applies to the behavior and the structure of those components and items.

Visualization of the design knowledge representation was built based on hierarchical tree structure. Tree structure has many advantages in such detailed hierarchical knowledge computation. Firstly it can be connected to the databases to retrieve and store new data; secondly its visual structure is flexible and expandable; designers can hide or show more details; thirdly it has a hierarchical structure which is useful in displaying the knowledge of any complex product. An example of the adopted tree structure is shown in Fig.8.

The knowledge databases are categorized in six major parts: (1) general project information includes project details, requirements, objectives, constraints, and clients' details (2) general design knowledge includes design domains, products, components, items, behaviors, functions, structures and structure items (3) specific design knowledge includes sample products-components, behaviors, functions, and structures, sample components-items, behaviors, functions, and structures, sample items-behaviors, functions,

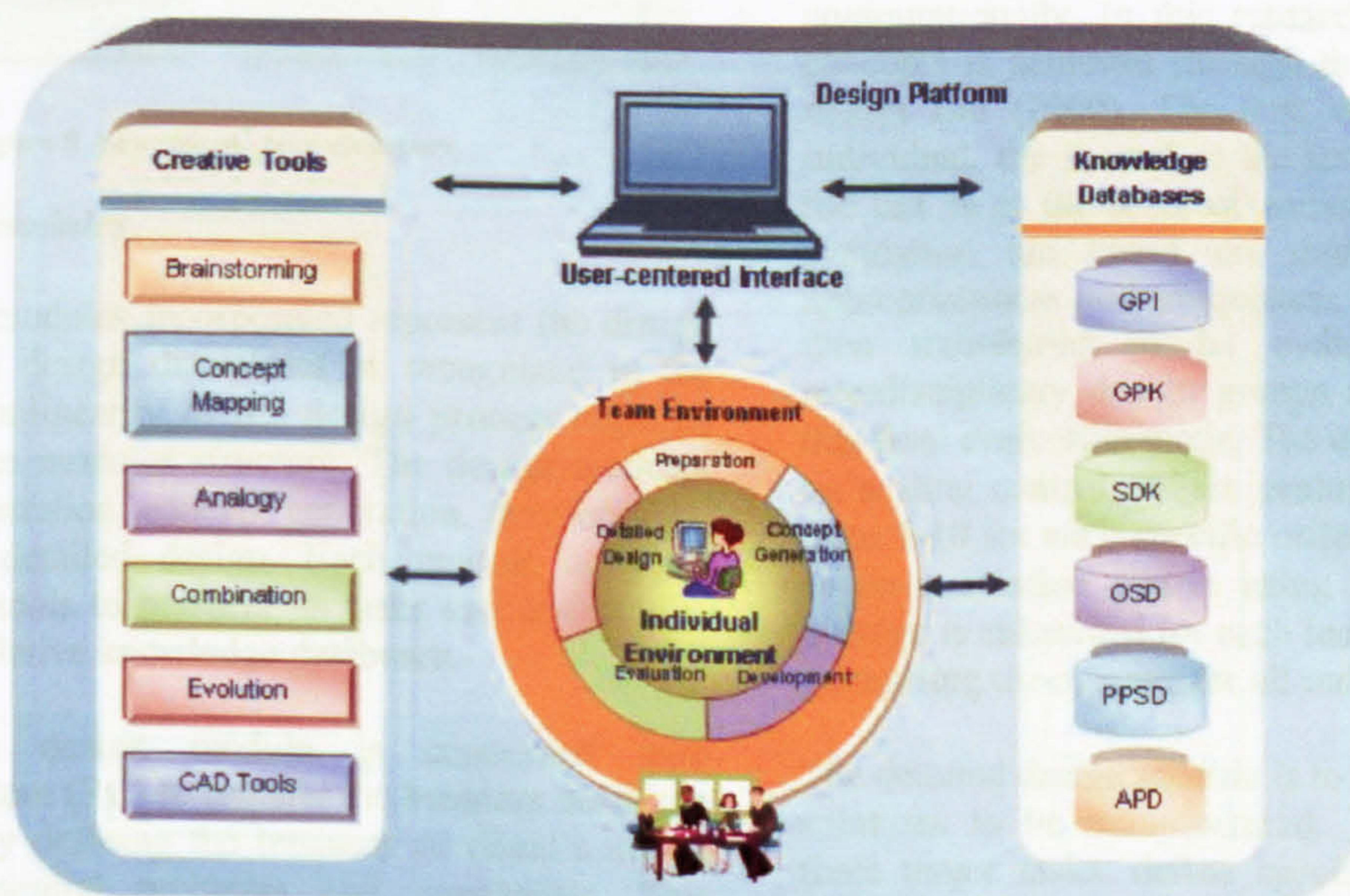


Figure 7 Proposed generic (CDT) framework

and structures (4) other sample designs includes sample products, components, and items designed by other designers with all their related features (5) previous projects sample designs includes samples of previous projects of that organization (6) active projects database acts as the working memory of the system where all the alternative solutions created for active tasks are stored temporarily to be retrieved and used through those design tasks till they are finalized.

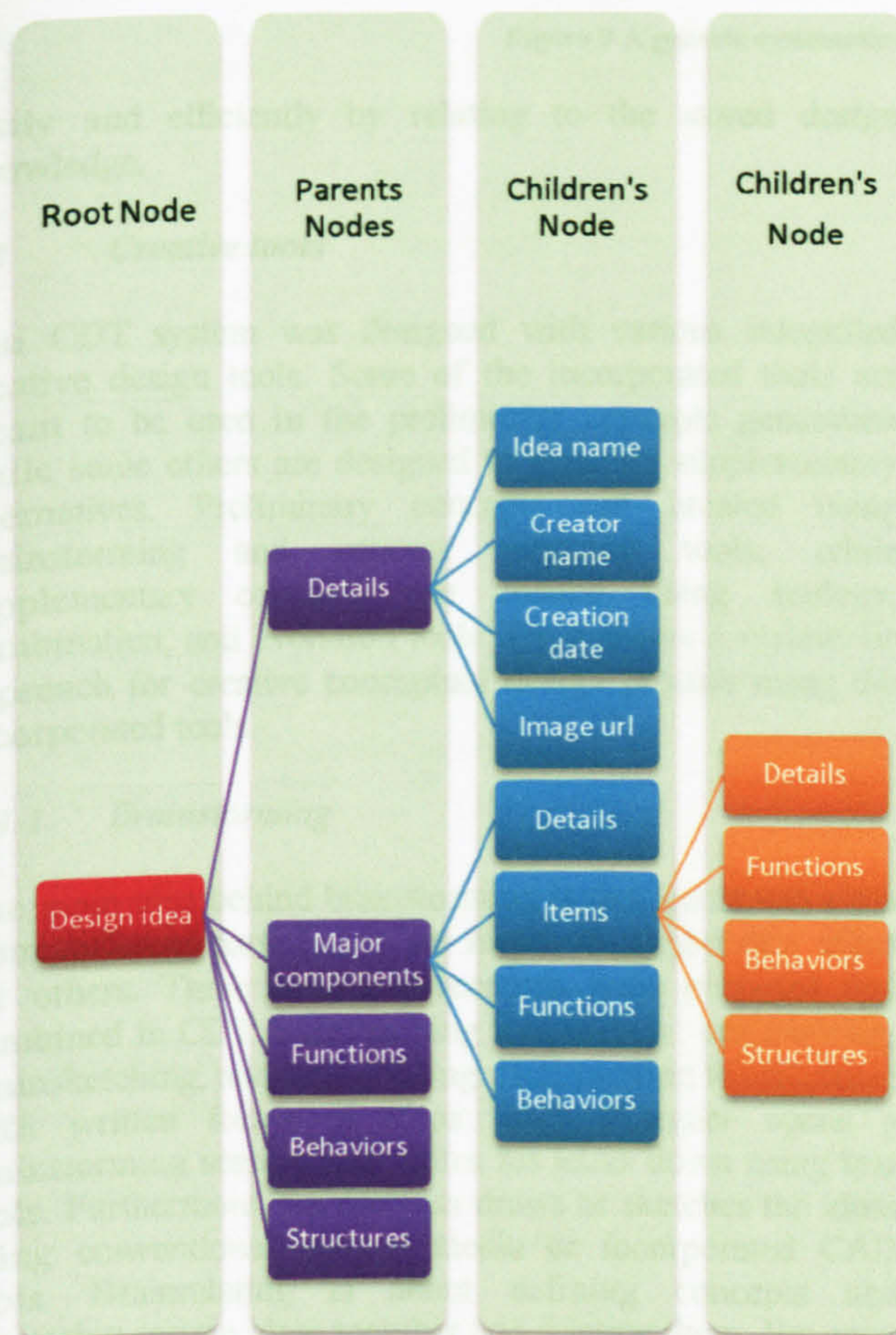


Figure 8 An example tree structure

3.2 Design modules

The five design modules incorporated represent the design process for most design disciplines as recognized in the literature. The nonlinearity of the design process required flexibility in those modules structure. The design modules included are preparation, concept generation, development, evaluation, and detailed design. Each module activates specific creative tools to perform its tasks and connects to the appropriate relative knowledge databases.

The preparation design module is concerned with requirements capture (RC) to transfer the business need into design strategy by defining the business or client's needs, requirements, essential problems and constraints. This module, primarily, consists of a range of tasks designed to

ensure that the appropriate data type and structure is identified and included in the related databases; client's meeting, search, problem formulation and reformulation were the main tasks incorporated in this design module. These tasks' interfaces are connected directly to the databases to store and retrieve the necessary data when required. Furthermore, interfaces to identify functional, behavioral, and structural features required for the design problem are included.

The module of concept generation is to develop those identified strategies and requirements into design proposals using the incorporated creative tools. This module encompasses three major tasks; to generate preliminary design alternatives, to generate supplementary design alternatives in order to widen the design solution space and to select the most creative ones through evaluation. This module is structured considering a multiple divergent convergent approach Liu et al (2003). The divergent step aims to widen the search for new ideas while the convergent step decreases the number of concepts to be developed according to the evaluation criteria and selection. This approach gradually increases the number of generated concepts beyond abstraction to be understood by designers therefore minimizing the number of abstract concepts to be considered without the compromise in the solution space.

The development module is to develop the selected ideas that have potential to be creative. This module covers three major tasks: selection, enhancement, and documentation. Selection is based on the appropriateness of concepts and the uniqueness of ideas. If the idea is selected further enhancements can take place by focusing on more detailing and identifying of new features or requirements. Documentation is to point out the idea precisely, its benefits, positive points, negatives, potential downsides, and supporting information.

The evaluation module is considered one of the most challenging creative design processes to be structured computationally. In this research the evaluation of design concepts is achieved through three inter-related evaluation modes Liu (2000). The first will be at the level of the individual, the second at the level of the design team, and the last is at the level of society. The first two levels of evaluation are based on multi-dimensional criteria of appropriateness and uniqueness. The successful results are then transferred to be evaluated by society where interdisciplinary design groups and others are involved in this final evaluation mode. The evaluation procedure is built on scaling controls where evaluators need to enter a value from 1-10 for each specific criteria. These values are saved as an evaluation matrix using Excel software where the average is calculated for each individual and for the team by calculating the average for all individuals.

The detailed design module is to finalize the selected design solutions to be manufactured. This module encompasses three major tasks: define specifications, produce working drawings, and 3D modeling. CAD and office tools are integrated with the CDT system to accomplish these tasks

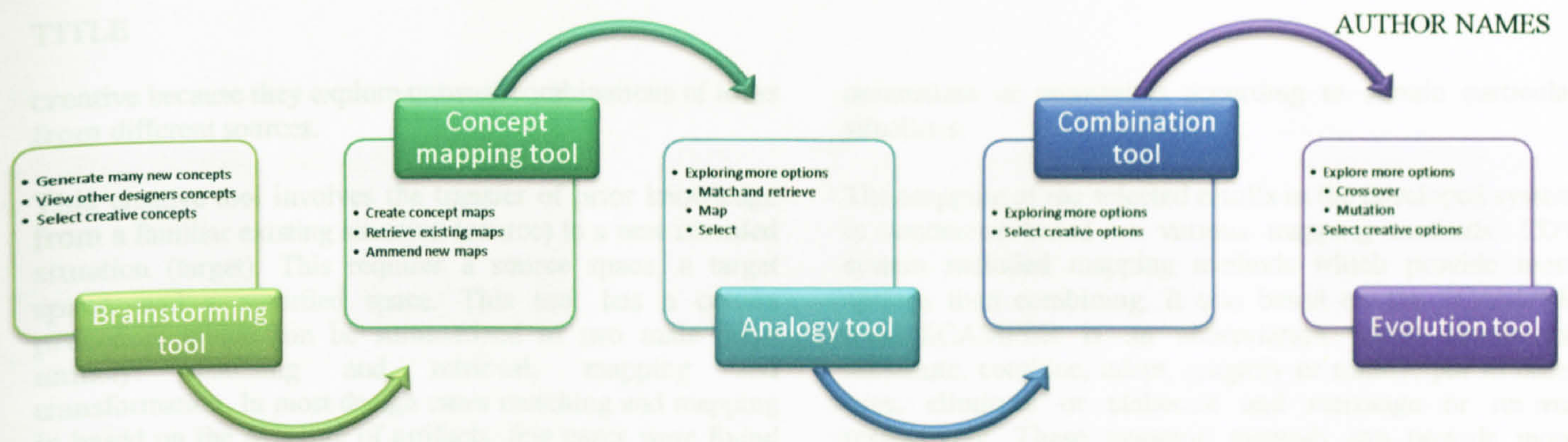


Figure 9 A generic systematic approach for creative conceptual design

easily and efficiently by relating to the stored design knowledge.

3.3 Creative tools

The CDT system was designed with various integrated creative design tools. Some of the incorporated tools are meant to be used in the preliminary concepts generation while some others are designed to generate supplementary alternatives. Preliminary concepts are created using brainstorming and concept mapping tools, while supplementary concepts are created using analogy, combination, and evolution tools. Fig.9 shows a systematic approach for creative conceptual design process using the incorporated tools.

3.3.1 Brainstorming

The main idea behind brainstorming is that generated ideas from different participants are meant to trigger new ideas for others. Three various procedures were proposed and combined in CDT brainstorming tool namely: brainwriting, brainsketching, and brainrelating. Brainwriting is concerned with written forms of ideas; each designer opens a brainstorming session and writes his ideas down using text tools. Furthermore, the designer draws or sketches the ideas using conventional manual media or incorporated CAD tools. Brainrelating is about defining concepts and clustering certain ideas together and relating them. Hexagon diagrams in AXON commercial tool were used to build the hexagon diagrams in CDT brainstorming. The results of these three procedures are saved in the active project database as brainstorming ideas. Each idea has a unique number to identify it and the designer who created it with the date it was created. The details of these ideas can be retrieved and reviewed by other designers after the session is ended. In this way each designer at the beginning generates ideas without any influence from others, later on the idea generation process ideas generated by others are viewed and evaluated to select the most suitable ones for further development.

3.3.2 Concept mapping

The use of concept mapping tool is considered a way of externalizing ones learnt knowledge in a structural or hierarchical form. Since the representation of knowledge needs to be comprehended and used successfully; several

factors were considered in designing the CDT concept mapping tool. These factors are:

- The ability to store design data in a homogeneous representation which is utilized by all the incorporated tools.
- The ability to retrieve data using the developed conceptual mapping structure which is the hierarchical tree.
- The ability to build new concept maps based on new generated ideas.
- The ability to view all details concerning the idea either by expanding the tree view or by linking to other data sources such as image files, text files, and media files.

The retrieval of stored concept maps is achieved by connecting to the database and with a certain query statement the data is retrieved and presented in the conceptual tree view. The designer decides on the type of that query by first indicating if the concept's map relates to a product, a component, or an item. Furthermore, a certain object is picked from the chosen category to retrieve its concept map.

New concept maps can be built by using the provided buttons to add a root tree node (representing the design object); details tree node, component tree node, behavior tree node, function tree node, and structure tree node. This tree structure as mentioned earlier can be repeated for all components and items. This ability of constructing structured new concept maps provides flexibility for designers to add new knowledge to the CDT system but within the boundaries of the adopted design representation. Tree nodes can be linked to various data forms such as images, documents, and media.

3.3.3 Analogy

Analogies are meant to free up designers' thinking and change their views of the design problem. Analogical thinking can be used to explore new features such as new functions, behaviors, and structures of a design object. The abstraction of a design problem is very crucial in matching and retrieval of analogies and plays a significant role in successful analogies' mapping. Various domains can be used as the source of analogical reasoning either similar to the design problem or dissimilar. Sometimes analogies recognized from dissimilar domains proved to be more

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creative because they explore unusual combinations of ideas from different sources.

This creative tool involves the transfer of prior knowledge from a familiar existing situation (source) to a new revealed situation (target). This requires a source space, a target space, and a modified space. This tool has a certain procedure which can be summarized in two main steps namely: matching and retrieval, mapping and transformation. In most design cases matching and mapping is based on the structure of artifacts, few cases were found to be based on the behavior or function of these artifacts. The computation of this tool can be presented based on Gero (2000) work as follows:

- Matching and retrieval: in this step the object with the highest similarity is retrieved for further processing.

$$SIM(D_T, D_S(i)) = \max_k SIM(D_T, D_S(k)) \quad (1)$$

where $SIM(*,*)$ is a real function which measures the degree of similarity between its parameter spaces.

$D_S(i)$ is the i -th source design state space

D_T is the target design state space.

- Mapping and transformation: in this step mapping adds some design variables from the i -th source design state space to the target design state space and then transforms the result of this operation into a modified design space D^m .

$$D^m = \tau(D_T \cup M(D_S(i))) \quad (2)$$

where M is a mapping operation

τ is a transformation operator.

In the CDT system the functions that measure similarity for matching and retrieval of analogies are based on one or more of the identified design features. It is built on finding similarities between functions, behaviors, and/or structures of design objects between the source design state space and the target design state space. Certain values for these features are identified by the designers to start the matching and retrieval according to them. Furthermore, the source design state space is chosen by the designer by deciding on the categories to search in such as sample products, sample components, sample items, any other source like images for example, or all of the mentioned categories. Searching all of the provided categories can be more useful in analogies but can cause some overloads in memory.

The originality in the analogical tool incorporated in the CDT system is its capability to match and retrieve design objects based on multi parameters. For example objects can be matched and retrieved using a single parameter, double parameters, or all behavior, function, and structure parameters. This approach constrains the search results and focuses the solution in specific directions. Afterwards these constraints can be relaxed and fewer parameters can be used to retrieve data. Therefore the CDT system provides flexibility in strengthening and relaxing the analogical

parameters or constraints according to certain particular situations.

The mapping of the selected results in the developed system is conducted based on various mapping methods. CDT system included mapping methods which provide more options than combining. It was based on the SCAMPER tool. SCAMPER is an abbreviation which stands for substitute, combine, adapt, magnify or minify, put to other uses, eliminate or elaborate and rearrange or reverse respectively. These mapping methods can provide more design options to consider. The designer can choose one of these methods each time and display the result, then change the method and see the mapped options again till a satisfying mapping outcome is achieved.

3.3.4 Combination

The combination tool is built on combining two or more different samples, components, or items to come up with a new one, or to combine two or more different features' values to create a new feature. When implemented; this tool can provide designers with more combination alternatives which might trigger a hidden creative idea.

This technique can be achieved on a structural, functional, and behavioural level. Four methods of combination are identified in the CDT system: systematic combination, tree random combination, vertices random combination, and total random combination. The four methods are based on the tree design representation described earlier. In systematic combination method the trees are chosen in order and the combination is achieved systematically between the different trees and vertices one by one. Tree Random Combination method is based on choosing the trees randomly but the combination between those trees vertices are conducted systematically. In the vertices random combination method the vertices are chosen randomly but the trees are chosen systematically. Finally in the total random combination method the trees and the vertices are chosen randomly. The computation of the four types of combination is as follows:

- *Systematic Combination*

$$\begin{matrix} n & k \\ \{ \{ u_{ij} \} \} \\ j=1 & i=1 \end{matrix} \quad (3)$$

where n = number of vertices in each tree
 k = number of trees

- *Tree Random Combination*

$$\begin{matrix} n & k \\ \{ \{ v_{g(i)j} \} \} \\ j=1 & i=1 \end{matrix} \quad (4)$$

where g is a permutation on $\{1, 2, 3, \dots, k\}$
 ** (choosing the trees randomly)

- *Vertices Random Combination*

$$\begin{matrix} n & k \\ \{ \{ v_{if(i)} \} \} \\ j=1 & i=1 \end{matrix} \quad (5)$$

where f is a permutation on $\{1, 2, 3, \dots, n\}$

**** (choosing the vertices randomly)**

• *Total Random Combination*

$$\{ \{ v_{g(i)f(j)} \} \}_{j=1}^n \quad (6)$$

where g is a permutation on $\{1, 2, 3, \dots, k\}$

f is a permutation on $\{1, 2, 3, \dots, n\}$

**** (choosing the trees and vertices randomly)**

The described methods were incorporated in the CDT system and the designers were given the choice to select the combination method according to their preference. Furthermore, these methods can be applied to pre-selected design alternatives by the designers, or it could be applied on the design samples stored in the databases and the results are displayed to evaluate and select the appropriate ones for further development.

3.3.5 Evolution

Evolution has been used as an optimiser in most cases, and as an explorer in recent cases concerning conceptual designs. The second option is adopted in the CDT system. This tool involves two main processes, namely cross over and mutation. Cross over is achieved at some selected parts (nodes) of a design tree structure between two or more designs (parents). It can be conducted at the level of components or features. Transformation (Mutation) is the alteration of one or more feature variables using transformational operations such as re-coloring, re-shaping, re-sizing, or changing materials. The computation of the evolution tool is as follows:

- Cross over is the crossing between parts of the structure from two or more parents. It can be modeled as:

$$S_{new1} = [S_{parent1} - \dot{S}_{parent1}] \cup \dot{S}_{parent2} \quad (7)$$

$$S_{new2} = [S_{parent2} - \dot{S}_{parent2}] \cup \dot{S}_{parent1} \quad (8)$$

where \dot{S} is part of the structure
 S is the whole structure

- Transformation (Mutation) is the alteration of one or more structure variables by an external process. It can be modeled as Gero(2000) described:

$$S_{new} = \Phi_m(S_{existing}) \quad (9)$$

where Φ_m is a transformation operator

Two main issues which are considered crucial in such a creative tool are: a good design knowledge representation which enables the uncovering of a wide range of alternatives, and the relaxing of constraints which can produce more creative alternatives. By using the tree design knowledge representations described earlier, this tool can be applied to any design knowledge available in any design process. In the CDT system a collaborative evolutionary

tool is incorporated which requires more human interaction with the process to replace the fitness functions. The designers were also provided with the flexibility of choosing the evolutionary process to be conducted and the design objects which are used as the parents in the evolutionary tool. The tool can be started, paused, and stopped during the evolutionary iterations. Moreover the evaluation of the suitable generations is achieved by the designers. The main aim of using the evolutionary tool in the CDT system is to provide a wide range of different solutions. Through regular utilization of the evolution tool more alternatives are created, and the exploration solution space is increased.

4. Implementing the CDT Creative Design Tools system

The substantial advantage of implementing the CDT system is that it provides a holistic integrated flexible creative design environment to assist designers in exploring more creative solutions through their design processes. The implementation of the CDT system as a web application offered many advantages over other types of systems:

- It provides consistency in the user interface for all users wherever they are located.
- The similarity of design knowledge accessed by designers in various locations because any change in the data is reflected to all users.
- Collaboration can be more efficient through the direct access to similar design knowledge to overcome the disadvantages of the synchronous/asynchronous ways of collaboration if the users are located in geographical areas with time differences.
- System updates are reflected immediately to all users and is conducted at one single station which will minimize the cost and time spent on updating processes.

The main function of the CDT interface is to explore more design alternatives with the assistance of the incorporated creative tools to reach creative solutions for design tasks. Broadening of the design solution space is achieved through the interaction between the design groups and the CDT system knowledge, tools and processes. The accomplished creative solutions are based upon the clients and designers knowledge identification, proposed conceptual alternatives, and creative tools applied. The evaluation of the most creative solutions is achieved at the individual, team, and society level with two major criteria in mind; appropriateness and uniqueness. Furthermore, it enables design groups to collaborate at the early stages of design through the identification of knowledge which is reflected to all design group members and the concept generation process which utilizes the various tools to increase the variety of alternatives stored in the solution space which were produced by all members of the design group. This variety of alternatives helps opening new channels for exploration.

In order to validate the CDT system a case study was used to reveal the capabilities of this system. A concept generation process was subjected to the use of the various creative tools and the identified knowledge in the system.

3.1 Case study: creative concept generation

To validate the system a case study is used to demonstrate the creative design tools focusing on the identification of requirements and the exploration of the alternatives generated by the application of the various tools incorporated. The design group should be aware of the problem task and the business requirements to be able to identify the necessary design knowledge required. Previous to proceeding with the creation of concepts the system formulates the problem based on the data collected through client meetings and search. The developed CDT system has the capability to display the stored data to be amended and updated through the design task by the design group members and to create design alternatives based on the tools and methods chosen by the design group members through the system interaction with the design knowledge database resources. These alternatives are evaluated by the design team members to choose the most promising ones to be further developed. According to the identified design requirements and the formulation of the design problem the design team starts generating concepts and solution alternatives through brainstorming, concept mapping and analogy tools. These generated ideas are stored in the active problem database (working memory) to be used extensively for exploration by the supplementary tools and to be viewed by all design group members. This working memory acts like a reservoir for ideas generated by all the members. These ideas are evaluated by the team and the result of the evaluation sessions are displayed as a summary report descending from the most creative options to the less creative ones. The design group members select the most creative desirable alternatives with high potential to be explored with the combination and evolution tools. The combination and evolution tools make use of the hierarchical structure of ideas to perform its enclosed methods. The system can be fed with selected alternatives or it can use its integrated selection procedures to retrieve options from the database resources to generate and display more options for the design team members for selection. A system scenario is detailed in Fig.10.

The following are the main phases conducted by the design team members to explore creative conceptual design alternatives for the present case study:

1. The design group members update the databases by identifying new required knowledge for the active design problem through search, and client meetings. These updates or additions are reflected immediately to the group members through the various design modules Fig.11 to fig.13 show examples of database updates.
2. The system starts formulating the problem from the active project database and represents the design requirements, constraints and related information in a

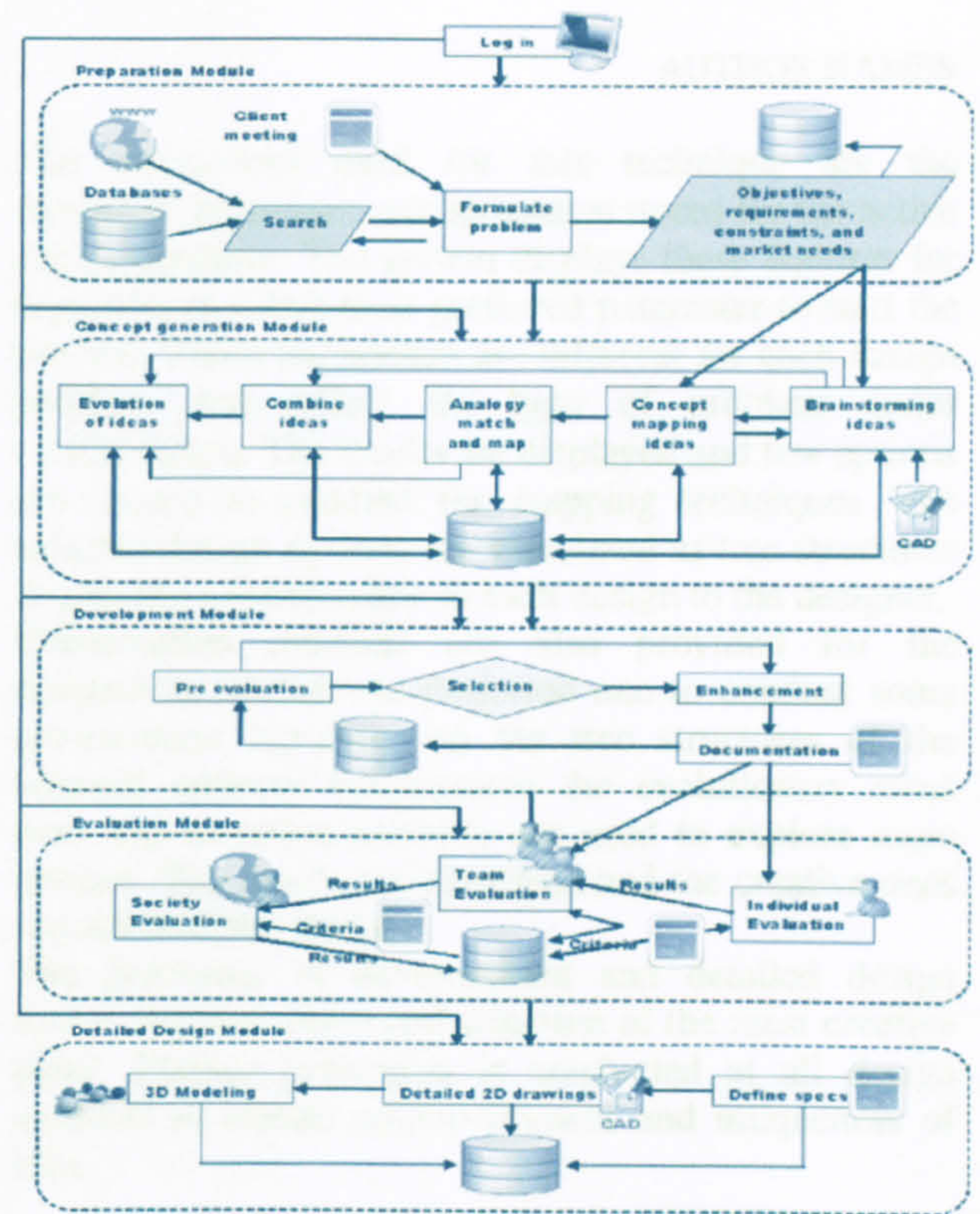


Figure 10 CDT system scenario

report form. This formulation supports the design team members in analyzing the problem and synthesizing ideas.

3. The design knowledge identified by the design team members assists the system in constraining the tools to use the precise knowledge in relation to the features chosen by the team members. For example if the parameter selected was a specific function, the system will use and display samples with that chosen function.

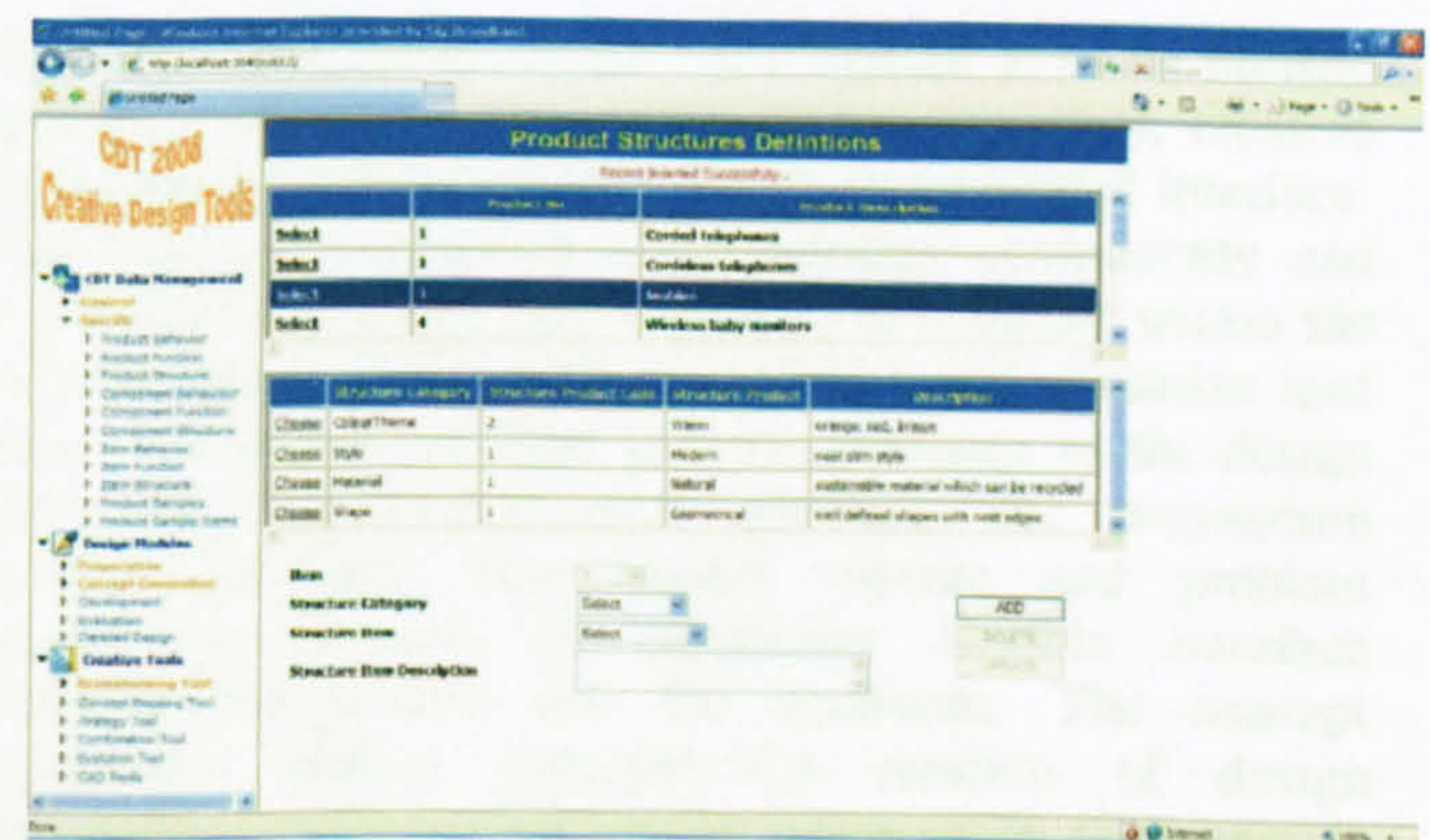


Figure 11 Product structures definition

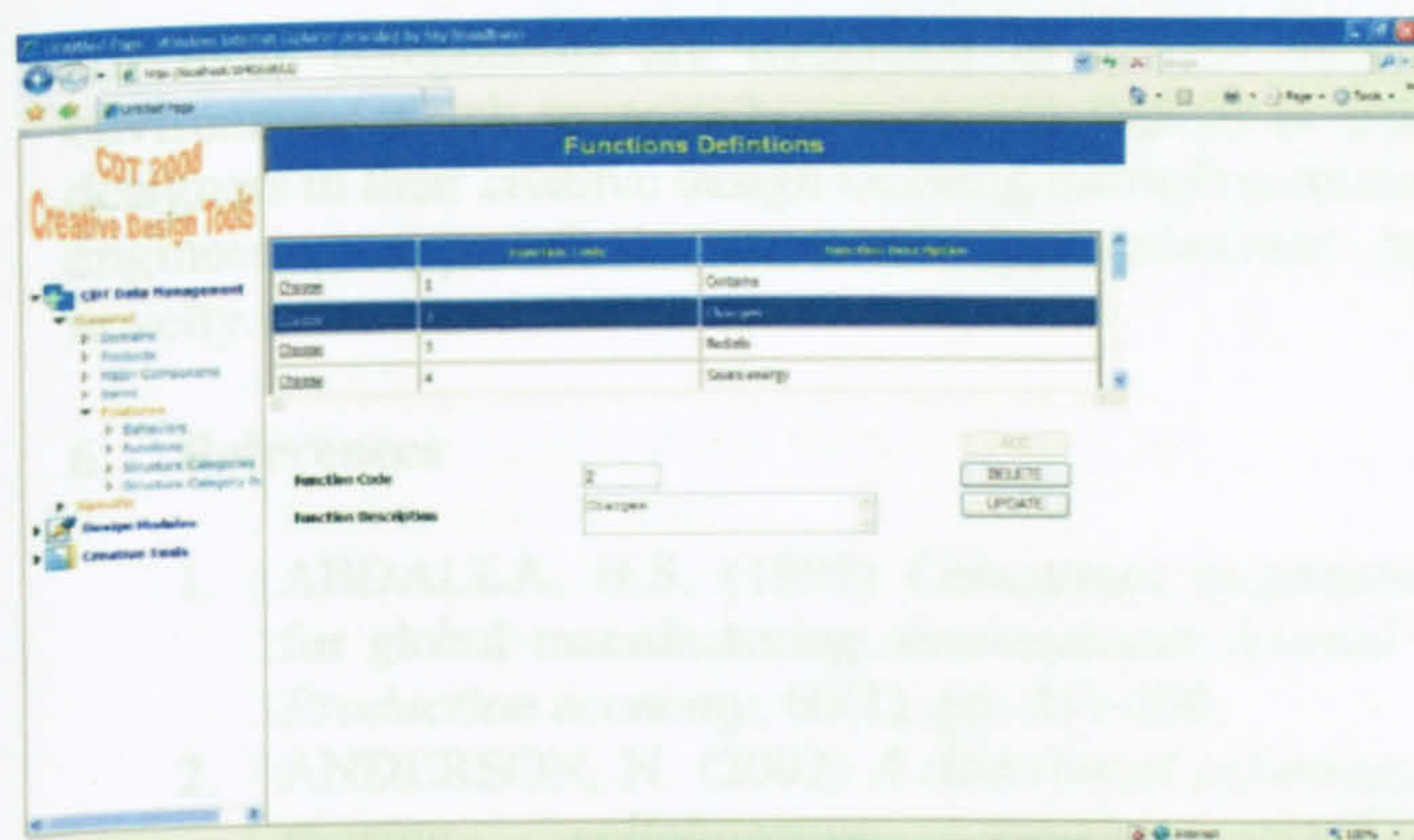


Figure 12 General functions definition

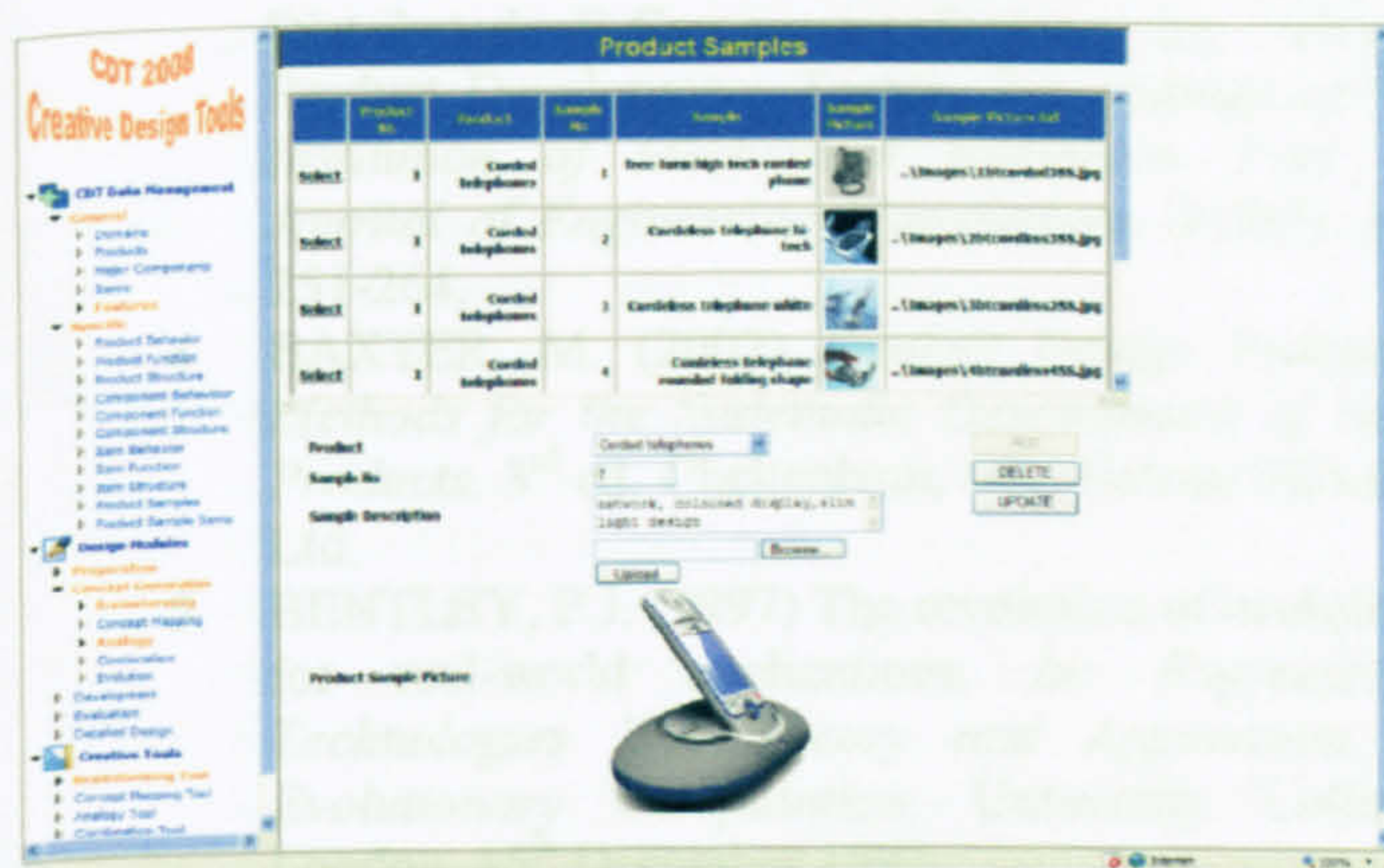


Figure 13 Product samples

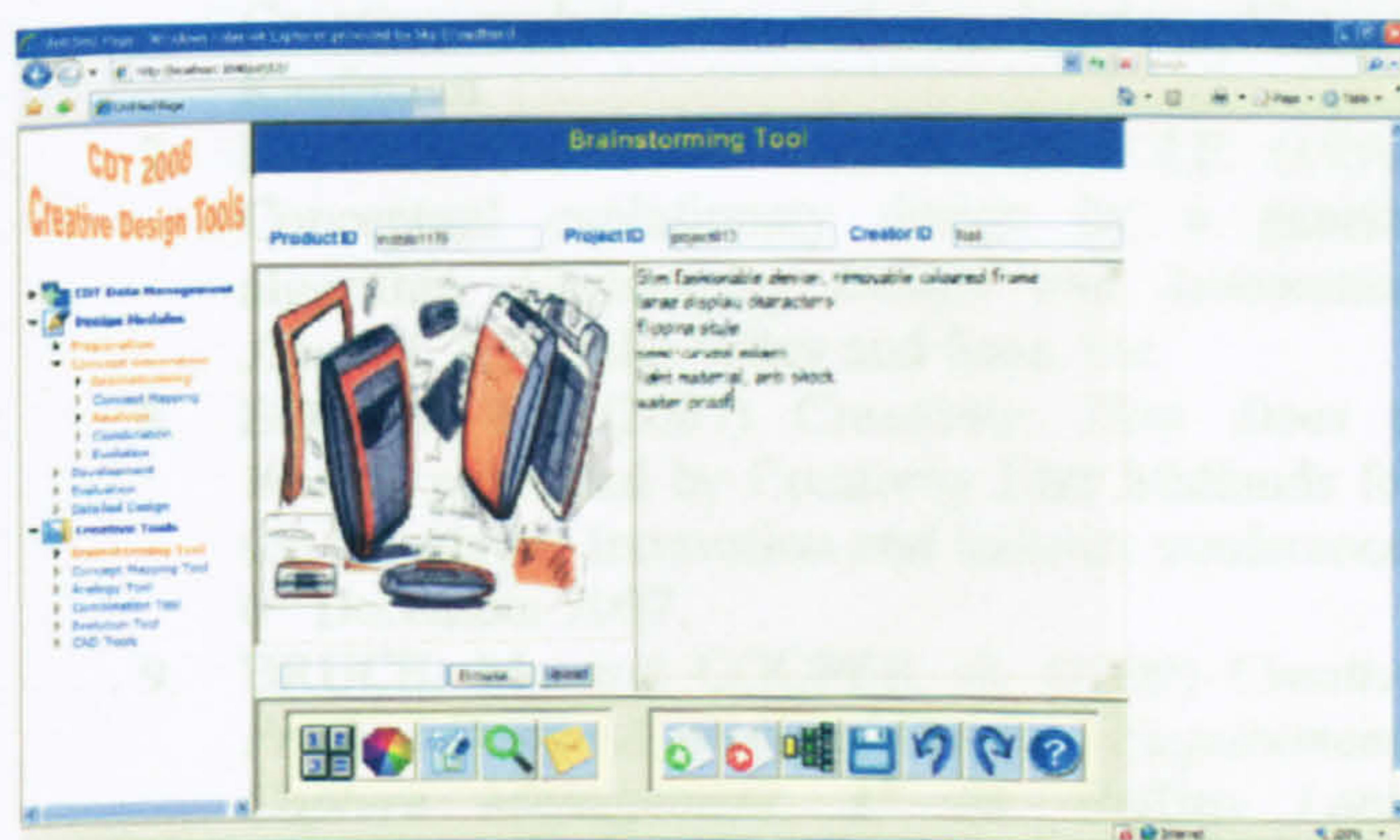


Figure 14 Brainstorming tool

4. The generation of ideas starts usually by brainstorming tool to let the designers generate many abstract alternatives to be considered. The generated ideas are stored in the active project database. The stored ideas can be retrieved by team members to select the most creative ones to develop. The ideas are displayed in a matrix form where each designer can enter his evaluation scale for the identified evaluation criteria built from the design problem requirements. Fig 14 shows a snap shot of the brainstorming tool.
5. Concept mapping is used to create the tree hierarchy structure for the selected ideas in order to be able to apply the other creative tools namely: combination and evolution.
6. Analogy matching and retrieval is used to retrieve more options from the stored design samples in the databases.

The parameters used for this technique are the functions, behaviors, and structures stored for the active design problem. The system displays these features for designers to select their preferred parameter to start the process. These parameters are different for each design problem and reflect the type of problem under consideration. The results are displayed and few options are chosen to conduct the mapping techniques. The selected design options are visualized as tree structures to provide a broad scope of each design to the designer.

7. Combination methods are also provided for the designer to choose the preferred one to conduct some combination iterations on the tree structures of the selected options. Furthermore the evolutionary cross over and mutation methods are used to explore more options. The results are displayed and the creative ones are selected and stored.
8. The processes of development and detailed design follow the evaluation and selection of the most creative ideas. Further evaluation is conducted at all design modules to ensure appropriateness and uniqueness of idea.

5. Conclusions

An integrated creative design tools system to enhance creative design thinking has been developed and presented in this paper. The developed system encompasses several parts including knowledge databases, creative tools, and design modules within a user friendly design environment. The design modules are composed of five interrelated modules which are: preparation, concept generation, development, evaluation, and detailed design. Moreover, the system is integrated with CAD software to increase the drawing capabilities, with AXON software to facilitate the hexagon diagramming in brainstorming, and with Excel software to assist the evaluation procedure.

The major originality of the CDT system is in its holistic approach that unites the various design processes, creative tools, and related knowledge within an integrated interface. The interaction between these various components can achieve more creative useful options to consider within the solution space, avoid re-designing costs and minimize lead time. The design modules provide guidance to the design teams in their implemented structure. The preparation module facilitates requirements capture and problem formulation through an interactive flexible interface between the system and the databases. The concept generation module supports the creation of design alternatives either by the design teams or by the system's incorporated creative tools to enlarge the problem solution space. The development module facilitates the development of the abstract design ideas to be stored, displayed, and recognized by all other design team members. The evaluation module provides evaluation criteria for individuals, teams, and society with displaying abilities of the evaluation results. Finally the detailed design module aids the final detailed drawings of the created options with specifications documents and 3D modeling.

All those components are integrated in a user friendly environment which supports human design aspects to assist designers in their creative design thinking through a creative engineering approach in terms of appropriateness and novelty.

6. References

1. ABDALLA, H.S. (1999) Concurrent engineering for global manufacturing. *International Journal of Production economy*, 60(1), pp. 251-260.
2. ANDERSON, N. (2002) *A distributed information sharing collaborative system (DISCS)*. Unpublished thesis (PhD), De Montfort University.
3. ANDERSON, N. and ABDALLA, H., (2002) A Distributed E-Commerce System for Virtual Product Development Teams. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 216(2), pp. 251-264.
4. BAXTER, M. (2002) *Product Design Practical Methods for the Systematic Development of New Products*. 3rd ed. Cheltenham, UK, Nelson Thornes Ltd.
5. BENTLEY, P.J. (1997) The revolution of evolution for real-world applications. In: *Engineering Technologies '97: Theory and Application of Evolutionary Computation*, University College London, 15th December 1997.
6. BENTLEY, P.J. and CORNE, D.W. (2002) *Creative evolutionary systems*. London, Morgan Kaufmann.
7. BENTLEY, P.J. and WAKEFIELD, J.P. (1996) Conceptual evolutionary design by a genetic algorithm. *Engineering Design and Automation Journal*, 2(3), John Wiley and Sons, Inc.
8. BODEN, M. (2007) *Creativity: How Does it Work?*, published by Creativity East Midlands for the Creativity: Innovation and Industry conference, 6th December 2007.
9. BRUCE, M., and COOPER, R. (2000) *Creative Product Design A practical Guide to Requirements Capture Management*. 1st ed. Baffins Lane, Chichester, England, John Wiley and Sons, Ltd.
10. BUZAN, T. (2002) *How to Mind map* 1st ed. London, UK, HarperCollinsPublishers Ltd.
11. CANDY, L. and EDMONDS E.A. (1997) Supporting the creative user: a criteria-based approach to interaction design. *Design Studies*, 18(2), pp. 185-194
12. CROSS, N. (1997) Descriptive models of creative design: application to an example. *Design Studies*, 18(4), pp. 427-455.
13. CROSS, N. (2000) *Engineering design methods: strategies for product design*. 3rd ed. West Sussex, John Wiley and Sons.
14. CSIKSZENTMIHALYI, M. (1988) Society, culture and person: a systems view of creativity. In: *STERNBERG, R.J. (ed), The nature of creativity*, Cambridge University Press, Cambridge UK (1988), pp. 325-339.
15. CSIKSZENTMIHALYI, M. (1996) *Creativity: flow and the psychology of discovery and invention*. New York, Harper Collins.
16. DAHL, D. W., CHATTOPADHYAY, A., and GORN, G. J. (2001) The Importance of Visualization in Concept Design. *Design Studies*, 22(1), pp. 5-26.
17. DARLINGTON, M. J., and CULLEY, S. J. (2004) A model of Factors Influencing the Design Requirement. *Design Studies*, 25(4), pp. 329-350.
18. DORST, K. (2001) Creativity in the design process: co-evolution of problem-solution. *Design Studies*, 22(5), pp. 425-437.
19. EYSENCK, H.J. (1994) The Measurement of Creativity. In: *BODEN, M., eds. Dimensions of Creativity*. USA, Massachusetts Institute of Technology, pp. 199-242.
20. GERO, J. (1990) *Design prototypes: a knowledge representation schema for design* [WWW]. Available from: <http://www.arch.usyd.edu.au> [Accessed 08/02/2005].
21. GERO, J. and KAZAKOV, V. (1999) Using analogy to extend the behavior state space in creative design. In: *GERO, J. S. and MAHER, M. L. (eds), Computational Models of Creative Design IV, Key Centre of Design Computing and Cognition*, University of Sydney, Sydney, Australia, pp. 113-143.
22. GERO, J. (2000) Computational models of innovative and creative design processes. *Technological Forecasting and Social Change*, 64, pp. 183-196.
23. GOMES, P., SECO, N., PEREIRA, F. C., PAIVA, P., CARREIRO, P., FERREIRA, J. L., and BENTO, C. (2006) The Importance of Retrieval in Creative Design Analogies. *Knowledge-Based Systems*, 19(7), pp. 480-488.
24. HEWETT, T. T. (2005) Informing the Design of Computer-Based Environments to Support Creativity. *International Journal of Human-Computer Studies*, 63(4-5), pp. 383-409.
25. HOEBEN, A., and STAPPERS, P. J. (2005) Direct Talkback in Computer Supported Tools for the Conceptual Stage of Design. *Knowledge-Based Systems*, 18(8), pp. 407-413.
26. HORI, K. (1997) Concept Space Connected to Knowledge Processing for Supporting Creative Design. *Knowledge-Based Systems*, 10(1), pp. 29-35.
27. HSIAO, S.W. and CHOU, J.R. (2004) A creativity-based design process for innovative product design. *International Journal of Industrial Ergonomics*, 34(August), pp. 421-443.
28. KOKOTOVICH, V. (2007) Problem Analysis and Thinking Tools: An Empirical Study of Non-Hierarchical Mind Mapping. *Design Studies*, 29(1), pp.49-69.
29. LIU, Y.-C., BLIGH, T., and CHAKRABARTI, A. (2003) Towards an Ideal Approach for Concept Generation. *Design Studies*, 24(4), pp. 341-355.

30. LIU, Y.T. (2000) Creativity or novelty? *Design Studies*, 21(3), pp. 261-276.
31. NAKAKOJI, K., YAMAMOTO, Y. and OHIRA, M. (2000) Computational support for collective creativity. *Knowledge-Based Systems*, 13(0), pp. 451-458.
32. PUGH, S. (1991) *Total Design*. 1st ed. Wokingham, UK, Addison Wesley.
33. SHNEIDERMAN, B. (2000) Creating Creativity: User Interfaces for Supporting Innovation. *ACM Transactions on Computer-Human Interaction*, 7(1), pp. 114-138.
34. SIMON, H.A. (1988) Creativity and motivation. *New Ideas in Psychology*, 6(2), pp. 177-181.
35. TSENG, C.J. ABDALLAH, H. (2004) A human-computer system for collaborative design (HCSCD). *Journal of Materials Processing Technology*, 155-156(2), pp. 1964-1971.
36. VAN DER LUGT, R. (2000) Developing a graphic tool for creative problem solving in design groups. *Design Studies*, 21(5), pp. 505-522.
37. WARD, T. B., FINKE, R. A., and SMITH, S. M. (1995) *Creativity and the Mind. Discovering the Genius Within*. London; New York, Plenum Press.
38. WON, P.H. (2001) The comparison between visual thinking using computer and conventional media in the concept generation stages of design. *Automation in Construction*, 10(3), pp. 319-325.
39. YIN, Y., VANIDES, J., RUIZ-PREMO, M. A., AYALA, C.C. and SHAVELSON, R. J. (2005) Comparison of Two Concept-Mapping Techniques: Implications for Scoring, Interpretation, and Use. *Journal of Research in Science Teaching*, 42(2), pp. 166-184.

APPENDIX B

INTERVIEWS QUESTIONNAIRE

1. Covering letter sent to designers before the interview.
2. Interview questions guideline.

Dear Sir/Madam

I would like to have between 5-10 minutes interview with your self regarding sharing some of our research findings concerning the various factors which enhance creativity among designers. The object of this exercise is to elicit independent and candid opinion not influenced by my presence. Please be assured about confidentiality of the given information.

I am doing a sponsored doctorate degree in this field within the creative product design and development team lead by Professor Abdalla.

Thank you for your cooperation.

Best regards

Feda' Salah

Creativity Interviews

1. Personal Details

Last Name: ■■■■■	First Name: ■■■■■
Age: 20-30	Gender: Male
Specialty: Product Design	Qualification: First degree
Working Experience: None	

2. What does creativity mean to you?

Ability to adapt and change surrounding situations into something different hopefully useful.

3. What techniques do you believe may stimulate creative design thinking?

Sample materials, look at other people work, look at different products in market, talk to other people, and brainstorming.

4. Describe the methods you apply to evaluate a design if it is creative or not?

Using keywords regarding the shape, function and other things cannot be explained. (list of unconscious criteria)

5. Explain the design process you follow when you work on a certain design problem?

Design brief + meeting with customers, produce some concepts, contact customers to evaluate and take feedback to continue with the process.

6. Mention the computer tools that you usually use in any design process and you find very helpful.

Alias studio tools, scanners.

7. Do you think computers enhance your work or delay it?

Enhances it for sure.

8. If you were given a certain design computation system that has evidence of stimulating designer's creativity, will you use it?

Sure will try it to see how it works.

9. What is the environment that you find more suitable for designers to stimulate their creativity?

Flexibility.

10. What comments would you like to add?

In the system the designer's job will be an evaluator more than a designer.

Thank you